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CDC 32470

PRECISION MEASUREMENT EQUIPMENT LABORATORY TECHNICIAN

(AFSC 32470)

Volume 4

Microwave Measurements, Standards/TMDE

Extension Course Institute
Air University

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Preface

THIS FIFTH volume of CDC 32470, *Precision Measurement Equipment Laboratory Technician*, will help you develop the skills you need for 7-level performance in the microwave area of the PME Laboratory. Chapter 1 gives an analysis of klystrons, microwave oscillators, microwave transmission lines and thermocouples. It also tells how to make the necessary computations using logarithms. Chapter 2 contains information on frequency measurement and standing-wave ratio measurements in the microwave region plus information concerning the 8620C Sweep Oscillator. Chapter 3 discusses information necessary for making microwave power measurements along with information on several units. Chapter 4 provides information on microwave attenuators, methods of performing attenuation measurements and swept frequency attenuation measurements. Chapter 5 contains information on the microwave accessories which are used in conjunction with the equipment discussed in the first four chapters.

Appendix A (Table of Common Logarithms) and Appendix B (Natural Sines, Cosines, and Tangents) are included, as they will be useful in helping you handle the problems in this volume.

There is one foldout printed and bound in the back of the volume for easy reference.

After you have applied the knowledge contained in this volume to actual job performance situations, your proficiency advancement to the next skill level in your AFSC should be easier.

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This volume is valued at 30 hours (10 points).

Material in this volume is reviewed annually for technical accuracy, adequacy, and currency. For SKT purposes the examinee should check the Index of ECI Study Reference Material to determine the correct references to study.

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CHAPTER 1

Microwave Principles

AS A PRECISION Measuring Equipment Specialist, you will be required to maintain and calibrate electronic equipment operating in the microwave range of the frequency spectrum. Representative items of such equipment will be discussed in succeeding chapters. However, to enable you to gain maximum benefit from such discussions, we must first discuss some of the principles of microwave theory. In this chapter, we will discuss certain mathematical concepts applicable to microwave theory, the operating principles of microwave transmission lines, and some common oscillators currently in use as microwave sources.

1-1. Microwave Mathematics

Knowledge of, and proficiency in, the use of the mathematics associated with microwave measurements is essential if you are to be able to convert those measurements to usable information. Therefore, you must have a thorough understanding of the mathematical processes used in computing the various quantities required.

Working with quantities of impedance, attenuation, power, etc., often involves the manipulation of very large or very small numbers. For such operations, logarithms provide an easy-to-use, accurate means of calculation. In addition to the basic operations of logarithmic calculations, our discussion will concern itself with the relationships between logarithms, power ratios, and decibels.

600. Indicate how to determine the logarithms of numbers using a table of common logarithm.

Logarithms. The principles of logarithmic computation greatly simplify the multiplication and division of numbers by reducing multiplication and division to addition and subtraction, respectively. This principle is used extensively in many computing devices, including the slide rule.

The logarithm of a quantity is the exponent to which a given number, called the base, must be raised in order to equal the quantity. For example, $100 = 10^2$. Therefore, 2 is the exponent/logarithm of 100 to the base 10; or, if $b = a^x$, X is the logarithm of b to the base a.

Because the decimal numbering system is the most commonly used, a system of logarithms has been devised utilizing 10 as its base. This system is called the Common System, and our discussion will limit itself to this system.

The logarithm of any number consists of two components, called the characteristic and the mantissa, and two separate operations must be performed to determine the complete logarithm. The first operation yields the characteristic. To find the characteristic of a number's logarithm, write the number in scientific notation, that is, a number between one and ten, raised to a power of ten. The power of ten is the characteristic of the logarithm.

Examples:

$2525 = 2.525 \times 10^3$ in scientific notation, and the characteristic is the power of 10, which is 3.
$682 - 6.82 \times 10^2$, characteristic is 2.
$2134.6 = 2.1346 \times 10^3$, characteristic is 3, etc.

The characteristic of a number less than one, a decimal fraction, is negative in sign.

Examples:

$0.7424 - 7.424 \times 10^{-1}$, the characteristic is -1, logarithmically expressed as 1.
$0.00253 = 2.53 \times 10^{-1}$, the characteristic is 3.

The second component of a logarithm, the mantissa, is found by using the table of common logarithms. A portion of such a table is shown in figure 1-1. Refer to this figure during the following discussion.

Follow these steps to determine the mantissa of any number.

(1) Find the first three significant digits of the number in the vertical column labeled "No."

(2) Follow the same line across the page until you intersect the vertical column under the fourth significant digit of the number.

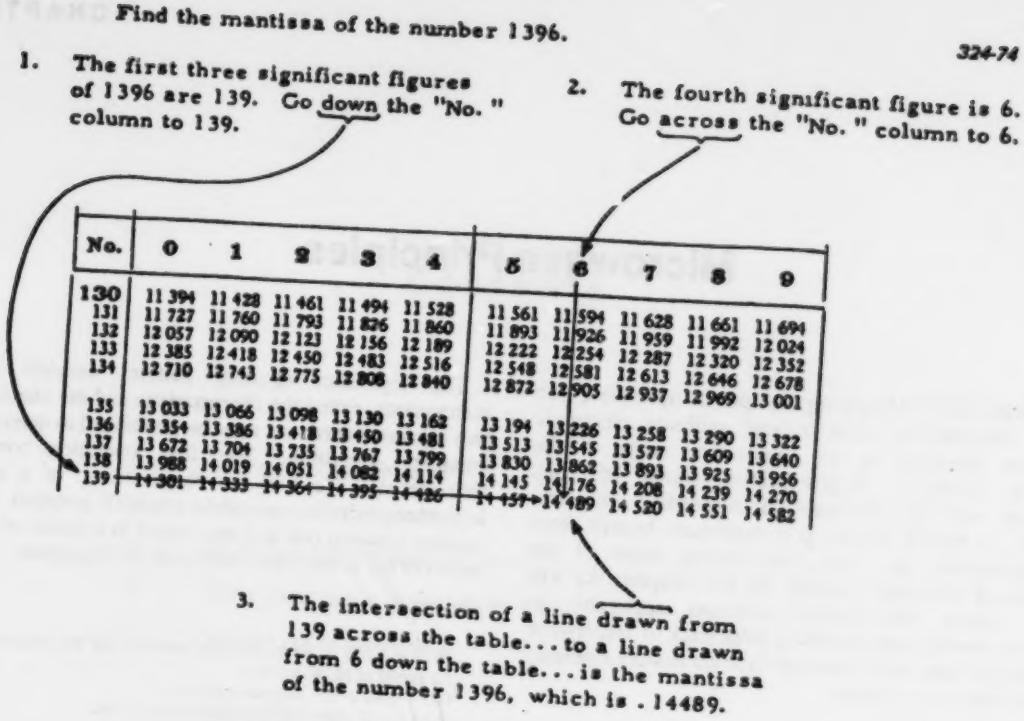
(3) The number found at this intersection is the mantissa of the number's logarithm.

Example: Find the mantissa of the number 1396.

(1) The first three significant digits of the number 1,396 are 139. Go down the "No." column to 139.

(2) The fourth significant digit is 6. Go across the page, on the same line, to the column under 6.

(3) The intersection of a line drawn from 139, across the table, to a line drawn from 6, down the table, is the mantissa, which is 0.1449.


Find the mantissa of the number 1396.
324-74
1. The first three significant figures of 1396 are 139. Go down the "No." column to 139.
2. The fourth significant figure is 6. Go across the "No." column to 6.
3. The intersection of a line drawn from 139 across the table... to a line drawn from 6 down the table... is the mantissa of the number 1396, which is .14489.

No.	0	1	2	3	4	5	6	7	8	9
130	11 394	11 428	11 461	11 494	11 528	11 561	11 594	11 628	11 661	11 694
131	11 727	11 760	11 793	11 826	11 860	11 893	11 926	11 959	11 992	12 024
132	12 057	12 090	12 123	12 156	12 189	12 222	12 254	12 287	12 320	12 352
133	12 385	12 418	12 450	12 483	12 516	12 548	12 581	12 613	12 646	12 678
134	12 710	12 743	12 775	12 808	12 840	12 872	12 905	12 937	12 969	13 001
135	13 033	13 066	13 098	13 130	13 162	13 194	13 226	13 258	13 290	13 322
136	13 354	13 386	13 418	13 450	13 481	13 513	13 545	13 577	13 609	13 640
137	13 672	13 704	13 735	13 767	13 799	13 830	13 862	13 893	13 925	13 956
138	13 988	14 019	14 051	14 082	14 114	14 145	14 176	14 208	14 239	14 270
139	14 301	14 333	14 364	14 395	14 426	14 457	14 489	14 520	14 551	14 582

Figure 1-1. Extract of table of common logarithms.

Note that the decimal point is always to the left of the first significant digit in the mantissa. This will be true for any number, regardless of the sign of the characteristic. Note, also, that the position of the decimal point in the number for which the logarithm is being determined has no bearing on the mantissa. The mantissa of the logarithm of a number is solely dependent upon the sequence of the significant digits within the number.

Example:

The number is 1374; the mantissa of its logarithm is 0.13799. For the number 13.74, the mantissa is still 0.13799, etc.

In cases where the number of significant digits is greater than four (when using a four-place log table), some interpolation is necessary. However, for most purposes, the closest mantissa for the given number will provide sufficient accuracy and precision.

The complete procedure for determining the log of a number is as follows:

(1) Determine the characteristic of the logarithm.

(2) Locate, in the table of common logarithms, the mantissa for the significant digits of the number.

(3) The complete logarithm then becomes a mixed decimal fraction, the whole number being the logarithm's characteristic, and the fraction being its mantissa.

Example:

Find the logarithm of the number 132.8.

$132.8 = 1.328 \times 10^2$. The characteristic is 2.

From the table, the mantissa of the number 1328 is 0.12320. The complete log is the characteristic plus the mantissa and is equal to 2.12320. (If the characteristic were negative, the log would be written as 2.12320).

A four-place table of common logarithms is provided in Appendix A of this volume for your use in determining logarithms. Use this table for your calculations.

Exercises (600):

Using the table of common logarithms, determine the following numbers.

1. 1756.
2. 92.65.
3. 1.603.
4. 839.4.

601. State how to determine to antilogs of numbers using a table of common logarithms.

Antilogs. If you are given the logarithm of a number and asked to find the number that it represents, reverse the procedure you used to find the log.

Follow these steps to find the antilog of a logarithm:

(1) Find the given mantissa in the table.

(2) Move horizontally to the left and extract three figures from the "N" column. These are the first three significant figures of the number.

(3) From the mantissa, move up the column to the top of the page and extract the fourth number.

(4) If you combine steps 2 and 3, you have a four-digit number. See figure 1-2 for an example of taking the antilog for the mantissa of the logarithm.

Example: Find the number represented by the mantissa 0.09864.

(1) Find the mantissa in the table.

(2) The first three significant figures are in the "NO." column across from the mantissa.

(3) The fourth figure is directly above the mantissa.

The digits represented by the mantissa 0.09864 are 1255.

The next step is to use the characteristic to determine where the decimal point will be placed to form the proper number. First, place the decimal point after the first digit, and then multiply this figure by a power of 10 that is equal to the characteristic.

Example:

Logarithm	*Number*
2.10415	127.1
0.11361	1.299
6.09061	1.232×10^{6}
$\bar{3}.07954$	1.201×10^{-3}

In cases where the mantissa of the log is not listed exactly in the table, you will need to estimate for rounding-off purposes.

Example:

Refer to the common log tables and extract the antilog of 2.13140. Since the given mantissa is nearer to 0.13130 than to 0.13162, the antilog would be 1.353×10^{2}. If, in finding the antilog, the mantissa falls exactly between those appearing in the table, select the larger number. The antilog of 1.46783 would be 2.937×10^{1}, because the mantissa 0.46783 is exactly between 0.46776 and 0.46790; therefore, the larger digits are selected.

Exercises (601):

Use the table of common logarithms to find the antilogs of the following numbers.

1. 4.51268.

2. 0.60831.

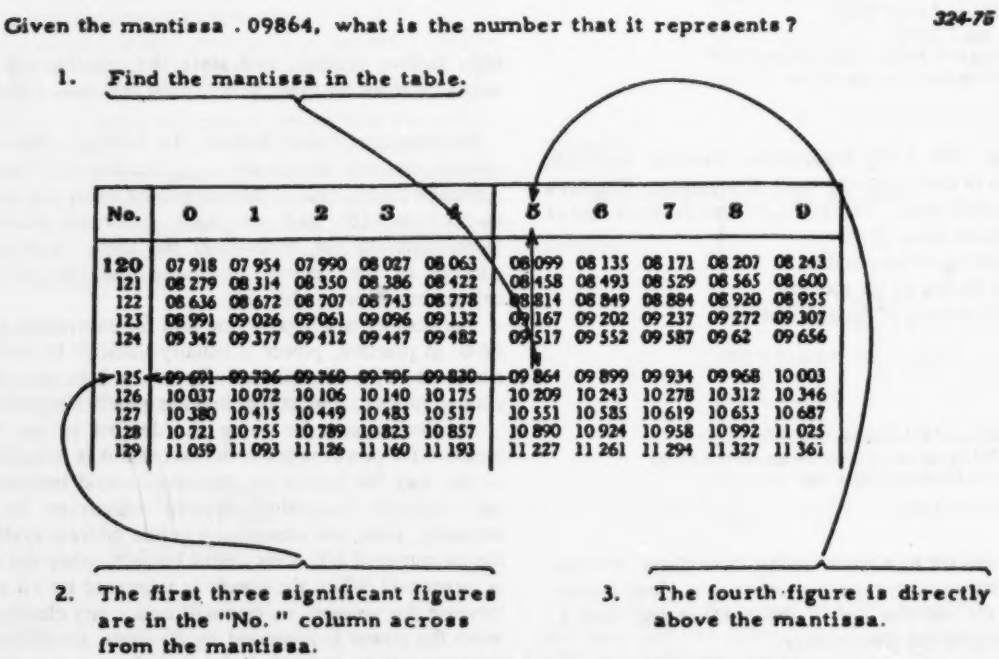


Figure 1-2. Extract of table of common logarithms.

3. $\bar{2}.22220$.

4. 3.00087.

602. Indicate how to use logarithms to perform mathematical computations.

Computations Using Logarithms. We have seen how logarithms may be determined and their antilogs extracted. Let us now discuss the various uses of logarithms in mathematical computations.

Multiplication. To multiply numbers, add their logs and find the antilog of the sums.

Example:

To multiply 9617 × 528.2
Determine the log of 9617 = 3.98304
Determine the log of 528.2 = 2.72280
Add the two logarithms 6.70584
Find the antilog of 6.70584, which is 5.08×10^6
Then the product of 9617 × 528.2 equals 5.08×10^6

Division. Find the log of the dividend and the log of the divisor. Subtract the log of the divisor from the log of the dividend. The antilog of the difference is the answer.

Example:

Divide 6742 by 126
Determine the log of 6742 3.82879
Determine the log of 126 2.10037
Subtract the logs 1.72842
Find the antilog of 1.72842, which is 5.351×10^1
Then 6742 divided by 126 equals 53.51

Extracting roots using logarithms. Another important use of logs is in extracting the roots of a number. The laws of exponents still apply. Therefore, to find the sixth root of a number, follow these steps.

(1) Find the log of the number.
(2) Divide the log by the root (6).
(3) Find the antilog of the quotient.

Example:

Find $\sqrt[6]{424}$
Determine the log of 424 which is 2.62737
Divide 2.62737 by the root (6), and the answer is 0.43790
The antilog of 0.43790 is 2.741×10^0
Then $\sqrt[6]{424}$ equals 2.741

Raising numbers to a power using logarithms. The last basic computation is to raise a number to a given power. The rule is to find the log of the number and then to multiply the log by the given power.

Example:

Find the value of 16^8 using logs.
Determine the log of 16 which is 1.20412
Multiply 1.20412 by the given power (8), which equals 9.63296
The antilog of 9.63296 is 4.295×10^9
Then 16^8 equals 4.295×10^9

Exercises (602):

Use logarithms to find the products or quotients of the following numbers.

1. 7.63×10^4 multiplied by 1.231×10^{-4}.

2. 748.0×10^{12} multiplied by 0.001108×10^{-11}.

3. 6677 divided by 44.55

4. 184.4 divided by 21.37

5. Use logarithms to find the fourth root of 480

6. Use logarithms to raise 12 to its seventh power

603. Define decibel, and state the relationship which exists between decibels, power gain and loss, and dBm.

Decibels and Power Ratios. The decibel is the common unit of measure for power amplification or attenuation. Although many items of test equipment today are calibrated in decibels (dB), and yet, many otherwise experienced technicians do not understand the term. Actually, the concept of the decibel is simple and the method of calculating dB is not difficult.

The decibel is a logarithmic unit for expressing a power ratio. In practice, power is usually difficult to measure at audio or radio frequencies. By using logs and dB, the computations to find gain or loss are greatly simplified.

Another reason for using the decibel as the unit of measure for power ratios is the fact that it is actually based on the way the human ear perceives sound intensity. The ear responds logarithmically to variations in sound intensity. Take, for example, a public address system that has an output of 100 watts. What happens when the volume is increased? When the power is increased by 10 watts to increase the volume, no one will notice any change. Even when the power is increased by 20 watts, no difference in loudness will be noticed. Only when the power is increased by 25 watts will the difference be noticed. The ear can just

detect a difference between two sound intensities when they differ by one *decibel*, or a 25 percent increase.

A decibel can be defined as that gain in loudness just noticeable to the human ear, an increase in power of 25 percent. The *power ratio* expressed in decibels is equal to 10 times the log (to the base 10) of the power ratio. The power ratio, in watts, is expressed as power output divided by power input.

$$db = 10 \log \frac{\text{power output}}{\text{power input}} \text{ or } 10 \log PR$$

Power input is the energy applied to a circuit and power output is the result of the circuit operation in terms of *gain* (amplification) or *loss* (attenuation). In the basic formula, there are three variables: dB, power input, and power output. If any two are known, the third may be found.

Example:

An amplifier has an input power of 10 mW. The output power is 20 mW. What is the gain in dB of the amplifier?

Solution:

$$dB = 10 \log \frac{P \text{ output}}{P \text{ input}}$$

$$dB = 10 \log \frac{20 \text{ mW}}{10 \text{ mW}}$$

$$dB = 10 \log 2$$

$$dB = 10 \ (0.30103)$$

$$dB = 3.0 \text{ or } 3.0 \text{ dB}$$

From this example, we can see another interesting thing about dBs and power: That power is doubled for a 3 dB gain. (The inverse is true for attenuation.)

The sign associated with the number of decibels indicates whether input or output is greater; thus, a negative sign means power output is less than power input. An attenuator is an example in which the input is greater than the output. Whether there is a gain or loss can usually be determined by inspection, and the appropriate sign (plus or minus) applied. When the power output is smaller than the power input the resulting division gives you a fraction. To avoid using colog, negative logarithms, simply invert the fraction and place a minus sign before the dB term.

Example:

An attenuator has an input power of 20 mW. The output power is 10 mW. What is the loss in dB of the attenuator?

Solution:

$$dB = 10 \log \frac{P \text{ output}}{P \text{ input}}$$

$$dB = 10 \log \frac{10 \text{ mW}}{20 \text{ mW}}$$

$$-dB = 10 \log \frac{20 \text{ mW}}{10 \text{ nW}} \text{ (invert)}$$

$$dB = 10 \log 2$$

$$-dB = 10 \ (0.30103)$$

$$-dB = 3.0 \text{ or } -3.0 \text{ db}$$

By manipulating the logarithmic equation for decibels, you can solve for either of its terms, when the other two terms are known.

So far the decibel has been considered strictly as a unit or measure for power ratios. Decibels cannot be used to represent actual power but only the ratio of one power to another. In many electronic applications it is desirable to have a logarithmic expression that represents actual power, not a power ratio. To fulfill this requirement, the dBm was developed. The dBm is a "coined" term used to represent power levels above or below 1 milliwatt.

Minus dBm represents power levels below 1 milliwatt, and plus dBm represents power levels above 1 milliwatt. In other words, a dBm is a specific amount of power, and 0 dBm is equal to 1 milliwatt. Briefly stated, the amount of power in a given number of dBm is the power which results if 1 milliwatt is amplified by that number of dB. For example: 40 dBm represents some actual power level, 40 dB above 1 milliwatt. On the other hand -10 dBm represents some power level 10 dB below 1 milliwatt. Conversely, it stands to reason that any power level may be expressed either as plus or minus dBm, depending on whether the power level is more or less than 1 milliwatt.

Example:

A power level of 20 mW is how many dBm?

Solution:

$$dBm = 10 \log \frac{P \text{ large}}{1 \text{ mW}}$$

$$dBm = 10 \log \frac{20 \text{ mW}}{1 \text{ mW}}$$

$$dBm = 10 \ (1.30130)$$

$$dBm = 13.0130 \text{ or } 13.0 \text{ dBm}$$

Example:

A power level of 0.2 mW is how many dBm?

Solution:

$$dBm = 10 \log \frac{P \text{ large}}{1 \text{ mW}}$$

$$-dBm = 10 \log \frac{1 \text{ mW}}{.2 \text{ mW}} \text{ (invert)}$$

$$-dBm = 10 \log 5$$

$$-dBm = 10 \ (0.69897)$$

$$-dBm = 6.9897 \text{ or } 7.0 \text{ dBm}$$

$$dBm = -7.0$$

Remember, if the power level is greater than 1 mW, you will have positive dBms; and if the power is less than 1 mW, you will have negative dBms. The signs placed on dBms are of great significance. Be sure to use them carefully.

Exercises (603):

1. What percentage of increase in power must take place before the human ear will respond to the change in volume?

2. Why is the decibel a logarithmic function?

3. What ratio is represented by negative decibels?

4. What common device yields negative decibels?

5. What value of power is represented by 0 dBm?

6. A 7.2 dB attenuator has a 15 mW input. What is the output power, expressed in milliwatts?

7. If the input power to an amplifier is 3.2 mW, and the output power is 656 mW, what is the gain of the amplifier, expressed in dBs?

8. How many dBms are represented by a power level of 5 microwatts?

9. If the input to a 9 dB attenuator is −6 dBm, what is the output power, expressed in dBm and microwatts?

10. An amplifier has a gain of 37 dB, with an input power level of −23 dBm. When the output of the amplifier is fed to an attenuator, which has a loss of 27 dB and what is the output power expressed in microwatts?

1-2. Microwave Transmission Line Theory

You have previously studied the theory of transmission lines. In this section, we discuss only those related principles of transmission lines which directly apply to the microwave area of calibration and repair.

In the microwave area, you work primarily with coaxial transmission lines and waveguides. Various principles of transmission lines are used in the calibration of microwave devices. In the calibration of microwave devices, you will be concerned with characteristic impedance, frequency, wavelength, voltage standing-wave ratio (VSWR), reflection coefficient (Γ), impedance, and attenuation. Our discussions are centered about these terms and how they apply to waveguides and coaxial transmission lines.

604. Define the term "characteristic impedance" and indicate the elements which determine its value.

Characteristic Impedance. As you already know, impedance is defined as the opposition that a transmission line offers to current flow. This impedance is identified as characteristic impedance to indicate the impedance of a particular transmission line with certain physical and electrical characteristics. Characteristic impedance of a given transmission line is dependent upon the ratio of inductance and capacitance per unit length of transmission line. This ratio is a function of the spacing between the conductors and the dielectric material separating the conductors. As you can see, characteristic impedance is a design function and does not change; therefore, you cannot alter or change it. You must know the characteristic impedance of the line you are using and the effect it will have on the calibration system with which you are using the line.

From your past studies, you know that a transmission line possesses characteristics of series resistance, series inductance, shunt capacitance, and shunt conductance for each unit length of line. A unit length or section of a line can be represented for convenience as an equivalent network composed of all four distributed constants of the actual line. These constants per unit length of line are normally shown as lumped values, as seen in figure 1-3. You must remember that the lumped values of R, L, C, and G are merely convenient representations of properties that are actually distributed over the whole length of the line.

The distributed constants of a transmission line determine its operating characteristics which, in turn, affect the signal being transmitted over the line. We can demonstrate the meaning of characteristic impedance by using a tee section of resistance to represent the lumped constants of each section of the line. Because of the complexity of the mathematics, we will use resistances alone to show the derivation of the characteristic impedance. If we use only resistances, the mathematics is much simpler, and the meaning of the result is the same as far as characteristic impedance is concerned.

For our discussion, refer to figure 1-4, A, and let the three resistances of the pi section represent one section of a transmission line. Assume that each resistance is equal to 300 ohms. By simple calculation of the total resistance, you can see that the input impedance of the line is 200 ohms. Now connect a second section ahead of the first, making the line a two-section line. This is shown in figure 1-4, B. The first section now acts as a 200-ohm resistance across the second section. Again, combine the resistance of the first and second sections in the manner shown in the figure, and the impedance now becomes 175 ohms for the two sections of line. Now let us add a third section to the line as shown in figure 1-4, C. The first two sections act as an equivalent

175-ohm resistance across the third section. Combining the resistances results in an input impedance of 173.3 ohms for a three-section line. If a fourth section of line is to be added, the resulting impedance is 173.2 ohms. You can see that as additional sections are added to the line, very little change is seen in the input impedance. You can see this in figure 1-5, where the input impedance is plotted against additional sections of transmission line. As you can see, the input impedance decreases toward a fixed value as the length of the transmission line is increased. This is true because, as each additional section is added to the transmission line, the amount of decrease of the input impedance becomes smaller and smaller. The input impedance cannot decrease to zero because of the series-distributed resistance. When the line is very long, the addition of more sections causes practically no change in the input impedance, and the impedance takes on a constant value. It is this constant value of impedance that is interpreted as the characteristic impedance of a line.

In the preceding discussion, we omitted the inductance and capacitance, for the sake of simplicity. For an actual transmission line, however, inductance and capacitance cause the characteristic impedance to vary with frequency. The change of the characteristic impedance is not great enough, however, to become a source of difficulty.

Exercises (604):

1. Indicate the factors which determine the characteristic impedance of a transmission line.

2. When does a transmission line assume its characteristic impedance?

3. How does varying the frequency of an applied signal affect the characteristic impedance of a transmission line?

4. As more sections are added to a transmission line, the input impedance is decreased. Which factor prevents the impedance from reaching zero?

605. Specify the relationships between the frequency, the wavelength, and the velocity constant of a transmission line.

Frequency and Wavelength. Frequency and wavelength are used to express events for some unit of time. You are familiar with the term frequency, but perhaps you are not quite so familiar with the term wavelength. As the number of cycles or events increases to that of the microwave frequencies, the frequency is usually identified in wavelength, or the distance a complete wave travels during the period (time) required for one complete cycle.

As you know, electromagnetic energy travels at the velocity of light in free space; consequently, the distance that electromagnetic energy travels during the period of one complete cycle is solely dependent upon the frequency. For example, a commercial power generator may rotate at a constant 60 revolutions per second. In the time that it takes the generator to rotate one revolution, the first portion of the cycle generated has traveled approximately 3100 miles. As the occurrence of the cycles increases (frequency increases and period decreases), the distance that each cycle travels during the period decreases. At a frequency of 10.0 GHz, the signal travels 1.18 inches for each complete period. A very definite relationship exists between frequency and wavelength. This relationship may be

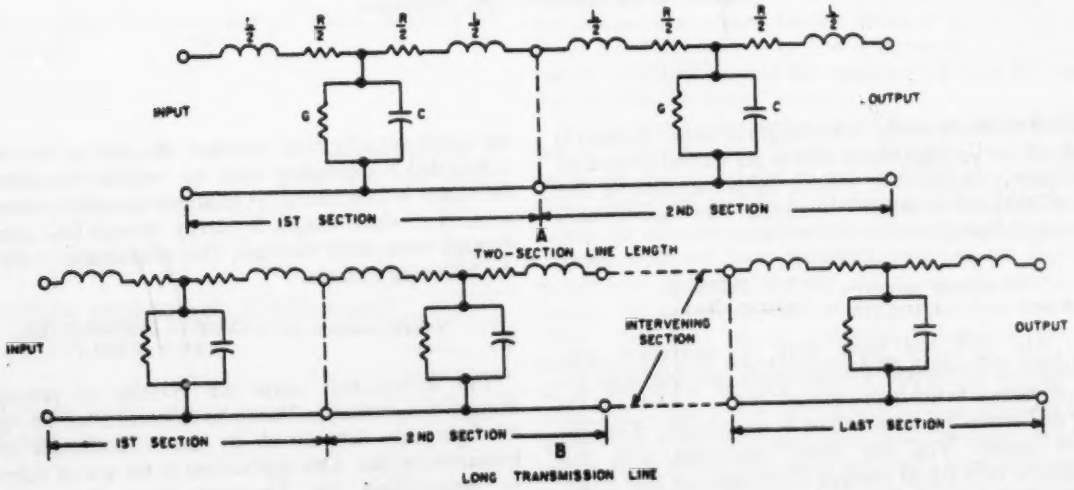


Figure 1-3. Equivalent network of a transmission line.

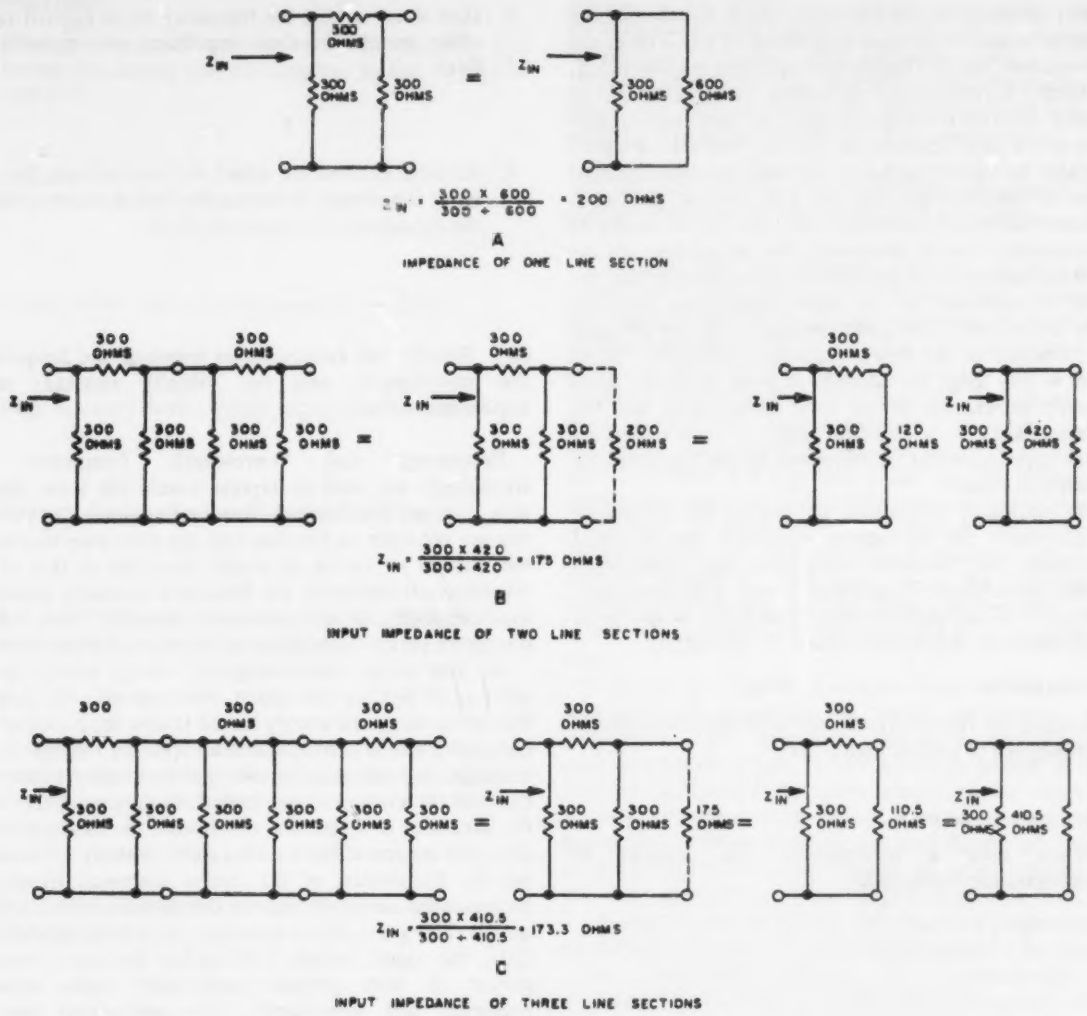


Figure 1-4. Calculation of input impedance.

expressed mathematically. Wavelength in meters is equal to the velocity of propagation in meters per second divided by the frequency in Hz. The velocity of propagation in free space is 300 million meters per second. The basic formula is given as follows:

$$\text{Wavelength (meters)} = \frac{300 \times 10^6 \text{ meters/sec}}{\text{frequency (Hz)}}$$

You will find that most work in microwave area wavelength is expressed in centimeters, because they are more convenient to use than meters.

Our discussion has been related to wavelength of energy in free space. You are more concerned with the transmission of a signal through a transmission line in the laboratory rather than with transmission in free space. The transmission of a signal through a transmission line causes the signal velocity to be retarded. The amount the velocity is retarded is dependent upon the medium through which the signal is transmitted. A relationship exists between the velocity of electromagnetic energy through free space and through some other medium. This relationship is shown in the following formula:

$$\text{Velocity constant (K)} = \frac{\text{velocity of propagation (Vg)}}{\text{velocity of light (Vl)}}$$

The factors that cause the velocity of propagation through a transmission line to be different from the velocity of light are determined by the construction of the transmission line. One application in the use of velocity is in determining the frequency from measuring the wavelength on a transmission line. Because the velocity of propagation is less on a transmission line than it is in free

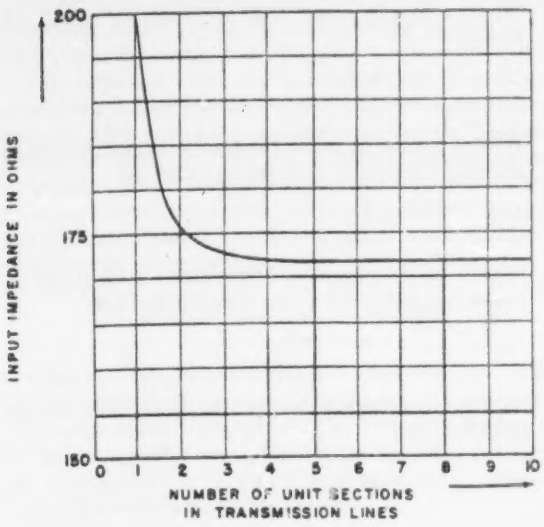


Figure 1-5. Input impedance versus transmission line sections.

space, the wavelength you measure is less than the actual wavelength of the applied frequency. The velocity constant of a transmission line can be determined by applying a frequency whose wavelength is known and then measuring the wavelength as it appears on the transmission line. The velocity constant of the transmission line is the ratio of the wavelength measured on the line to the wavelength in free space of the applied frequency. Here is the formula:

$$\text{Velocity constant of the line } (K) = \frac{\text{wavelength on line}}{\text{wavelength in free space}}$$

Exercises (605):

1. Indicate how frequency can be stated in terms of wavelength.

2. State the difference between the wavelength of a specific frequency in free space and the same frequency transmitted along a line.

3. What is the wavelength of a 10-MHz signal?

4. What is the frequency of a signal that has a wavelength of 2 centimeters?

606. State what various waves of energy affect the characteristics of the transmission line.

Traveling and Standing Waves. When energy is introduced onto a transmission line, the energy proceeds down the transmission line until it is either absorbed or reflected. Once the energy reaches the termination of the transmission line, it is absorbed or reflected, depending upon the characteristic of the termination.

Energy moving from the source toward the termination is known as the incident wave of energy. Energy that is reflected from the termination is known as the reflected wave of energy. Both of these waves are traveling; thus they are called traveling waves. We, therefore, can say that any wave moving along a transmission line is a traveling wave, regardless of the direction in which it is moving.

Once the incident wave has arrived at the termination or the end of the line, it is either reflected or dissipated by the termination. If the wave is not dissipated, it becomes a reflected wave and starts traveling back toward the source. The reflected wave, on its way back toward the generator, meets the incident wave. When the incident and reflected waves meet and are of the same phase, they combine to produce a voltage greater in amplitude than does either single wave. This wave that is produced by the combination of the incident and reflected wave is defined as a standing wave, because it does not move in either direction along the line with a given termination. The only thing that varies is the amplitude of the maximum voltage points as the reflected wave goes into and out of phase with the incident wave. We can also define the standing wave as the algebraic sum of the incident and reflected waves.

The presence or the absence of standing waves on a transmission line can be used to describe the transmission line. When the transmission line has no standing waves, it is described as being flat, nonresonant, or infinite. A line that has standing waves is defined as a resonant line. The fact that the line has standing waves indicates that the termination does not dissipate all of the energy, because it contains some reactance or is wholly reactive in nature. As you know, a reactance cannot dissipate power but only stores it and returns it to the line. The reactance of a reactor can be varied by varying the frequency. It is in this sense that the term "resonant" is used.

For any line to be nonresonant, it must not have standing waves. Therefore, it must be terminated in a pure resistance which is equal to the characteristic impedance (Zo). Under this condition, all the power is dissipated. In theory, an infinitely long line is also nonresonant.

From what we have discussed, you can see that the termination of a line greatly affects its characteristics. Briefly, let us look at some of the terminations and what effects they have on the transmission line. A practical termination which you use most often is one that dissipates all of the power incident upon it. When this occurs, the transmission line is flat and the line appears infinitely long to the source, allowing maximum power transfer. When a transmission line is terminated in either a short or an open, its characteristics change. In a line which is terminated with a short circuit, the standing wave of voltage is minimum at the short circuit, indicating that the incident

and reflected voltages are 180° out-of-phase. The standing-wave ratio is infinite, and 100 percent of the incident power is reflected back toward the source. The first voltage minimum, or node, occurs exactly one-half wavelength from the termination. The standing wave of current is 90° out-of-phase with the standing wave of voltage. In the opposite situation, where the line is terminated with an open circuit, the standing wave of voltage is two times the incident voltage at the termination. This means that the incident and reflected voltage waves are in-phase at the termination. The standing wave ratio is again infinite, and 100 percent of the incident power is reflected toward the source. The first voltage minimum, or node, appears one-fourth wavelength from the termination, and the first current node, or minimum, appears one-half wavelength from the termination. Whenever the transmission line is terminated by a resistance equal to the characteristic impedance, Zo, no reflections occur. Any mismatch in the termination is identified by the voltage standing-wave ratio (VSWR). This ratio is expressed numerically, and it can be determined from the following equation in terms of the amplitude of the standing wave maxima and minima:

$$VSWR = \frac{E_{max}}{E_{min}} = \frac{I_{max}}{I_{min}} = \frac{Z_{max}}{Z_{min}}$$

If you know the relationship of the termination with respect to the characteristic impedance, you can determine the VSWR from the following equations. When the termination resistance is greater than Zo, the following equation can be used:

$$VSWR = \frac{Rl}{Zo}$$

If the termination resistance is smaller than the characteristic impedance, you can determine the VSWR by the following equation:

$$VSWR = \frac{Zo}{Rl}$$

the value that you obtain from the division is the VSWR, and it is a ratio expressed with reference to unity. For example, a VSWR of 3 is a ratio of 3:1.

In practice, you, as a PME technician, will not be able to measure the voltage at the end of the line due to the physical aspects of the line used in the microwave frequencies. Instead, your measurements are confined to a small section of line which includes both the input and output ends. This limitation is overcome by first measuring the VSWR, then shorting the load and noting whether or not the positions of the nodes shift.

Exercises (606):

1. How are standing waves produced on a transmission line?
2. What condition exists when no standing waves are present?
3. What termination would produce a voltage minimum one-half wavelength from the termination?
4. Explain how a mismatched termination is identified by measuring the VSWR of the transmission line.
5. Identify transmission line waves, their source, and their direction.
6. Under what condition would there be no reflected wave on a line when there is an incident wave present?

607. State relationships between VSWR and reflection coefficient of a transmission line and apply these relationships.

Reflection Coefficient. As mentioned previously in our discussions, the reflected wave is generated as a result of reflection of the incident wave by the load. The ratio of the voltage of the reflected wave to the voltage of the incident wave, Er/Ei, is termed "the reflection coefficient of the load." This ratio is designated by the upper case Greek letter gamma, Γ. Mathematically, the reflection coefficient can be computed as follows:

$$\gamma = \frac{Zo - RL}{RL + Zo}$$

when Zo is greater than RL. However,

$$\gamma = \frac{RL - Zo}{RL + Zo}$$

when Zo is less than RL. When the line is terminated in an open or a short, Er = Ei; therefore, the VSWR is infinite and the reflection coefficient is 1. When the line is terminated in a resistance equal to Zo, Er is equal to 0. In this case the VSWR is 1:1, and the reflection coefficient is zero.

The reflection coefficient has both magnitude and phase and, therefore, is a vector quantity. Although the equations are expressed in terms of the situation at the load, the ratio Er/Ei of the voltages of the reflected and incident waves at a distance from the load can be termed the reflection coefficient at point d (distance from the load). When the line has zero attenuation losses, the reflection coefficient everywhere on the line has the same magnitude; and it equals the reflection coefficient at the load. However, when the line attenuation does not equal zero, then the reflected

wave becomes smaller and the incident wave larger with increasing distance from the load, causing gamma and the VSWR to decrease correspondingly.

The reflected wave on a transmission line can be considered as the fraction of the incident wave reflected from the load impedance and that it carries the fraction of power not absorbed from the incident wave by the load impedance. Since the power associated with each of these traveling waves varies as the square of their field strengths, you can determine the percent of power reflected from an arbitrary load impedance by:

$$\text{Percent of power reflected} = 100\,\frac{Er^2}{Ei}$$

Since you determine the extent to which the line and load are mismatched by measuring the standing wave ratio, a convenient relationship between the VSWR on the line and the percentage of power reflected and reflection coefficient can be expressed in the following mathematical equations. Study these relationships. As defined,

$$VSWR = \frac{E_{max}}{E_{min}}$$

$$VSWR = \frac{Ei + Er}{Ei - Er}$$

Dividing both the denominator and numerator by Ei:

$$VSWR = \frac{\frac{Ei + Er}{Ei}}{\frac{Ei - Er}{Ei}} = \frac{1 + \frac{Er}{Ei}}{1 - \frac{Er}{Ei}}$$

Since Er/Ei is the reflection coefficient, we can substitute and rewrite the equation:

$$VSWR = \frac{1 + \gamma}{1 - \gamma}$$

Transposing to solve for the reflection coefficient in terms of the VSWR, we obtain:

$$\gamma = \frac{VSWR - 1}{VSWR + 1}$$

Then, substituting,

$$\text{Percentage of power reflected} = 100 \times \frac{VSWR - 1^2}{VSWR + 1}$$

Due to the slight irregularities in its physical structure, any electrical component has some amount of stray capacitance and inductance. At low frequencies, this can be neglected. In the microwave region of the frequency spectrum, however, it can result in appreciable measurement errors. In this respect, the percentage of power reflected equation is one of a type that is particularly useful in that it permits the technician to obtain a higher degree of accuracy from his standards by taking into account the errors introduced by the standards themselves. The following problem demonstrates this point:

Example:

Suppose a power meter indicates that 2.3 mW is being dissipated by a standard transmission line load. What is the power output of the RF source if a VSWR of 1.5 is measured along this line? Since the standing waves exist on the line, the load is reflecting a fraction of the total power back to the generator; and the indication on the power meter is not a true indication. The true power output of the source can be determined indirectly by the following mathematical solution:

$$\text{Percentage of power reflected} = 100\,\frac{VSWR - 1^2}{VSWR + 1}$$

$$= 100\,\frac{1.5 - 1^2}{1.5 + 1}$$

$$= 100\,\frac{0.5^2}{2.5} = 100\ (0.2)^2$$

$$100\ (0.04) = 4\%$$

Now, since 2.3 mW comprises 100 − 4 or 96 percent of the total power (P_t), this data can be incorporated into the following equation of ratio and proportion.

$$\frac{100\%}{96\%} = \frac{P_t}{2.3}\ \text{mW}$$

or

$$P_t = \frac{2.30}{0.96} = 2.4\text{mW}$$

Exercises (607):

1. State the relationship between VSWR and gamma with an open or short termination in the transmission line.

2. How would you determine the actual output source power when VSWR of the line is 1.2 and 3.6 mW is measured at the termination?

3. What does the reflection coefficient of a transmission line represent?

4. If a transmission line is resonant, show why γ equals zero. Zo = 150 ohms.

608. Specify the various factors and conditions related to transmission line impedance, and compute the line impedance when given required data.

Impedance Along a Transmission Line. We know that

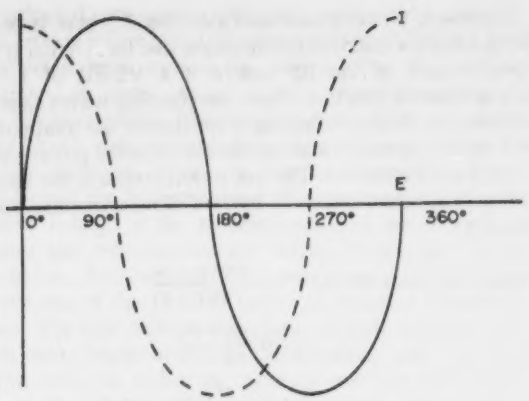


Figure 1-6. E and I relationships 90° out of phase.

the instantaneous voltage from a generator is equal to the peak voltage times the sine of the angle, or

$$E_{ins} = e_p \ (\sin \theta)$$

Using the sine as our standard or "norm" for voltage, we can introduce a term called the "normalized" value. This means that the voltage level at the time the generator completes, say, 30° of rotation, would be equal to sin 30° = 0.5; at 45°, the voltage would be equal to sin 45° = 0.707; and at 90°, equal to 1. This would seldom be the actual voltage at those times, but rather the normalized values. To obtain the actual values, we would have to multiply the normalized value by the peak value.

Now consider a case where a generator is producing a current which is 90° out-of-phase with the voltage. Plotting this information, we can illustrate the relationship between voltage and current in the manner shown in figure 1-6. Note that the current has the same waveshape as the voltage, yet it cannot be expressed by the same equation, since it is of maximum amplitude at 0° and 0 amplitude at 90°. The current waveshape follows the inverse function of the voltage, which is the cosine of the angle. Therefore, the normalized current is expressed as the cosine of the angle.

By Ohm's law, we know that R or Z = E/I. With a generator producing a sine wave of voltage and current in-phase, the normalized impedance would always be unity. However, in the condition shown in figure 1-6, where voltage follows the sine function and current follows the cosine function, the impedance follows the tangent function, since:

$$Z = \frac{E}{I} = \frac{\sin \theta}{\cos \theta} = \tan \theta$$

If a graph of the tangent function is plotted from 0° to 90°, a curve similar to that shown in figure 1-7 is obtained.

At 0°, the sine of the angle is zero, the cosine is unity, and the impedance is zero. At 45°, both the sine and the cosine are .707, and the impedance is unity. At 90°, the sine is unity and the cosine is zero. Now the ordinary laws of algebra leave division by zero undefined; but since the impedance is approaching positive infinity as the angle increases, we conclude for our own purposes that the impedance at 90° is positive infinity. It must be emphasized that, although the impedance varies throughout the range of zero to infinity each cycle, this is still the "normalized" value. The actual value of impedance at any given point is found by multiplying the normalized value by the characteristic impedance of the line, or Z = Zo (tan θ).

A complex plane of rectangular coordinates is used in figure 1-7 to represent the vector characteristics of the impedances which result from the phase difference between voltage and current. With this arrangement, we can easily identify the nature of the impedance. The ordinate of each point on the impedance curve from zero to 90° lies on the positive imaginary axis. Recalling from basic AC theory that the vectorial characteristics of voltage across an inductance places inductive reactance on the positive imaginary axis, we conclude that the impedance from zero to 90° ranges through all of the possible values of inductive reactance. The ordinate of each point on the impedance curve, from 90° to 180°, lies on the negative imaginary axis. The vectorial characteristics of voltage across a capacitance places capacitive reactance on this portion of the axis. Thus, the impedance from 90° to 180° ranges through all of the possible values of capacitive reactance. The type of impedance will repeat in this established sequence in keeping with the periodic nature of the voltage and current.

When the incident voltage and current waves are in-phase as they travel from the generator down the line, they both follow the sine function and the normalized impedance at all points along the line will be equal to 1, regardless of the actual values of the voltage and current. The numerical value of impedance is equal to the normalized value times the impedance of the medium conducting the voltage and current; in this case, the Zo of the line. The impedance in terms of the incident voltage and current is Zo (1) = Zo.

When the incident voltage and current reach a short, they immediately undergo a 180° phase reversal with respect to

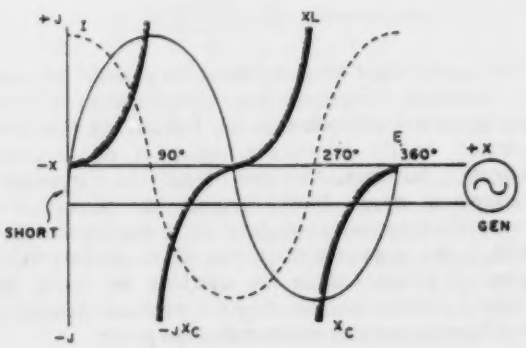


Figure 1-7. E, I, and Z relationships.

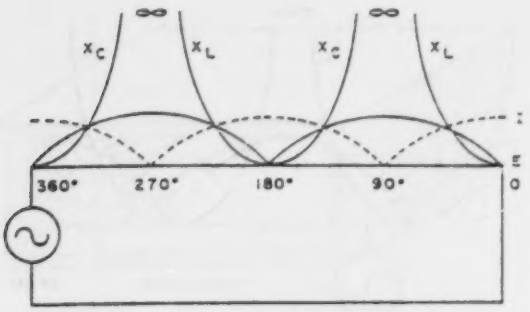


Figure 1-8. E, I, and Z distribution on a shorted line 1 wavelength long.

each other and travel back toward the generator. The incident voltage and current, which are in-phase, combine with the reflected voltage and current to produce standing waves of voltage and current, which are 90° out-of-phase. The short, then, has become the hypothetical generator of figure 1-8.

By referring to figure 1-7, you can construct a graph of the impedance at points along the line in the same manner as we illustrate standing waves. At the origin of the axis in figure 1-7, the current is maximum and the voltage is zero. These conditions coincide with those at the short on the line of figure 1-8. Rather than furnish coordinates to identify the types of impedance, they are simply labeled "X_L" or "X_C." A set of rules is given shortly to let you make correct identification of the type of impedance at any point on the line for any type of termination, without the use of a complex plane of coordinates.

By examining the impedance distribution along the line of figure 1-8, you see that the impedance is maximum when the voltage is maximum and minimum when the voltage is minimum. Ohm's law states that this will be the case. Thus, we can draw the impedance distribution for an open line with reference to the voltage standing wave only, as shown in figure 1-9.

From figures 1-8 and 1-9, the following rules can be applied to identify the type of impedance:

a. Starting from the load end of the line and looking toward the generator, an increasing impedance is an inductive reactance.

b. Starting from the load end of the line and looking toward the generator, a decreasing impedance is a capacitive reactance.

Remember, always start from the load.

In the following paragraphs, you will study problems which illustrate how the impedance can be calculated along the transmission line. Study these problems as they will help you to fully understand impedance along a transmission line and how it is affected by frequency.

Figure 1-10 illustrates quarter-wave shorted and open sections of line. At the generator, the standing waves take on the characteristics of a parallel and a series resonant circuit, respectively. If the generator in either figure is moved closer to the end of the line, the impedance that it "sees" will change. From this fact, it is possible to use a transmission line for any impedance that is desired by

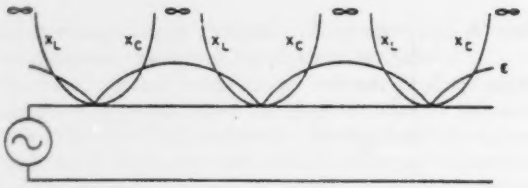


Figure 1-9. E and Z distribution on an open line 1½ wavelengths long.

simply changing the length of the line or the position of the generator along the line.

Whenever you are solving a problem, if possible, make a sketch of the relative positions of the standing waves on the line in question. In the following problem, determine the type and numerical value of input impedance to a 52-ohm line, "1/5" wavelength long, and terminated in a short.

Figure 1-11 is a diagram showing the voltage and impedance distribution from the data given. (The drawing need only be approximate.) From this diagram, you can see that the input impedance is an inductive reactance.

Since the numerical value is given by $-Zo\ (\tan \theta)$, you must determine the angle at point X. You can do this by regarding the point of minimum Z as 0°, and then finding the electrical distance between the short and point X in degrees. When this distance is given in wavelengths, as it is here, you can convert wavelengths to degrees by the following method:

Since

$$1/4\ \lambda = 0.25 = 90°$$

and

$$1/5\ \lambda = 0.20 = X°$$

Then, setting the above information into an equation of ratio and proportion:

$$\frac{0.25}{0.20} = \frac{90°}{X°}$$

$$0.25\ X = 18$$

$$X = \frac{18}{0.25} = 72°$$

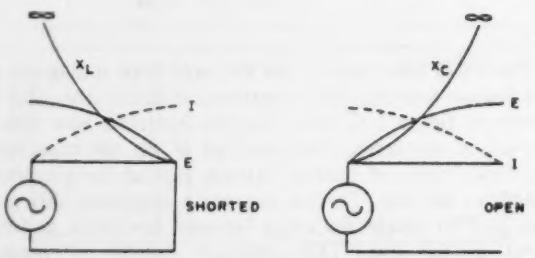


Figure 1-10. Quarter wavelength shorted line and quarter wavelength open line.

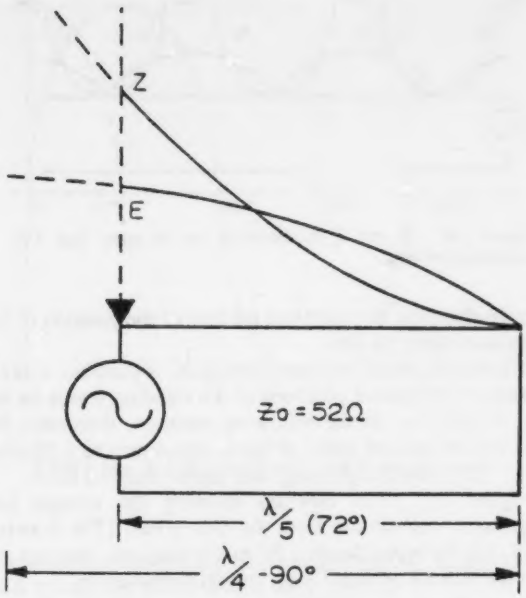


Figure 1-11. Diagram for problem 1.

From a table of trig functions (Appendix B): tan 72.0° = 3.0777. Inserting this value and the Zo of the line into the equation Z = Zo (tan θ), we have:

$$Z = 52\ (3.0777) = 160 \text{ ohms } X_L \text{ (approx.)}$$

Now, let's solve a problem where the input frequency to an open line 5.21-cm long is 4000 MHz. Let's determine the input impedance to the generator if the line Zo is 100 ohms. First, let's find the wavelength of the input frequency.

$$\lambda = \frac{30\ (\text{cm/sec})}{\text{f (gigahertz)}} = \frac{30}{4} = 7.5 \text{ cm}$$

The electrical length of the line is determined by the following ratio and proportion:

$$\lambda = \frac{7.5 \text{ cm}}{5.21 \text{ cm}} = \frac{360°}{X}$$

$$X = \frac{1875.6°}{7.5} = 250°$$

From this information, you can now draw a diagram of the voltage and impedance distribution on the line. This is shown in figure 1-12. Note that the generator now sees a capacitive reactance. The point of 0° on the capacitive reactance slope of interest extends beyond the electrical length of the line. So you can use a somewhat different approach to obtain the angle between this point and the input to the line. This approach consists of merely subtracting the electrical length of the line (in degrees) from the distance between the end of the line and the point of 0° on the capacitive reactance slope. The latter distance is

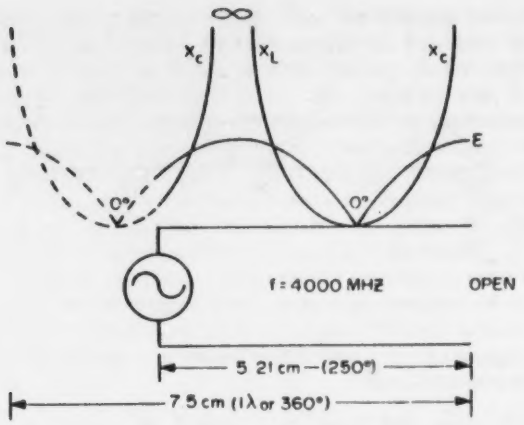


Figure 1-12. Diagram for problem 2.

three-quarter wavelength, or 270°. Hence, 270° − 250° = 20°. From a table of trig functions: tan 20° = 0.3640. Substituting this value and the Zo of the line in the equation:

$$Z = Zo\ (\tan \theta)$$

$$Z = 100\ (0.3640) = 36.4 \text{ ohms } X_c$$

Next, let's solve a problem to find the required length of a short circuited coaxial line which provides an inductive reactance of 250 ohms, if θ = 80 cm and Zo = 70 ohms. First, rearrange the equation Z = Zo (tan θ) to solve for tan θ,

$$\tan \theta = \frac{Z}{Zo} = \frac{250}{70} = 3.570$$

then

$$\text{arc tan } 3.570 = 74.4°$$

Setting this information into an equation of ratio and proportion,

$$\frac{360}{74.4} = \frac{80 \text{ cm}}{X \text{ cm}}$$

or

$$360X = 5{,}952$$

$$X = \frac{5{,}952}{360} = 16.5 \text{ cm}$$

From the solution, you have determined that a line 16.5-cm long would be required.

Exercises (608):

1. Differentiate between "normalized" values and actual values of voltage or current along a transmission line.

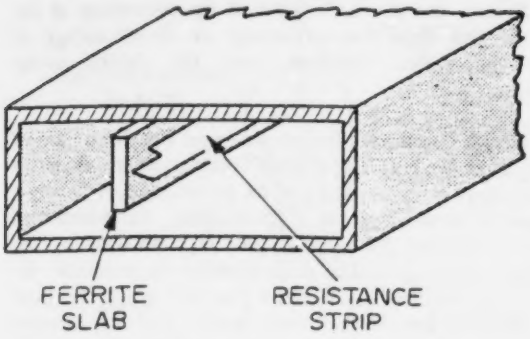


Figure 1-13. Ferrite isolator.

2. Under what condition would the normalized impedance be equal to the tangent function of the generator's angular displacement?

3. What vector characteristic results from a phase difference of 0° to 90° difference in-phase between voltage and current?

4. What is the impedance 34° from a shorted line? (Characteristic impedance equals 52 ohms.)

5. What is the normalized capacitive reactance at 180°?

6. Under what condition will the normalized impedance equal 1 at any point on the line?

7. State the general rule for identifying the capacitive reactance of a line.

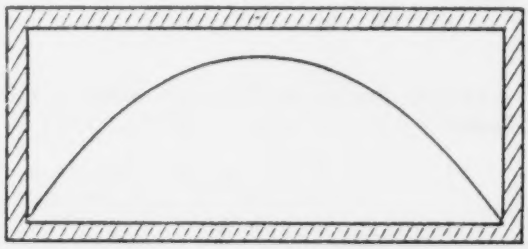
09. State the function of a waveguide isolator, specify ts principle of operation; and cite appropriate safety recautions.

Waveguide Isolators. A device used in most ransmission line hookups that you will be using is known s an isolator. This device is a waveguide element which ffectively permits transmission through the guide in one irection only. It can thus be used to prevent energy eflected from other elements in the microwave line from raveling backward through the guide to points where the reflected energy might adversely affect operation of vital circuit components, such as the klystron oscillator.

The nonreciprocal behavior of isolators depends upon certain peculiar properties of the magnetic ferrites. Because of their extremely high resistivity, ferrite materials do not normally have any appreciable effect on the propagation of high-frequency electromagnetic waves. If inserted within a waveguide, they are practically transparent to microwave energy traveling through the guide. However, in the presence of an externally applied DC magnetic field, the behavior of the ferrite is quite different. Within the ferrite, because of its unique magnetic structure, there is now definite interaction between the applied field and the magnetic field of the traveling microwave energy. This, in effect, changes the permeability of the ferrite. The result is some distortion or displacement of electric field of the traveling microwave energy. Moreover, the interactions are such that the permeability change in the ferrite is different for the two directions of microwave transmission. The electric field displacements, accordingly, are also different.

Look at figure 1-13, which shows a section of rectangular waveguide in which a thin slab of ferrite, which is typically a few inches in length, is placed in the off-center position. When a DC magnetic field is applied to the ferrite in a direction at right angles to the magnetic field of the traveling microwave energy, the magnetic field is displaced.

Figure 1-14 shows the normal electric field intensity distribution in a cross-section of a rectangular waveguide. The ferrites with the applied magnetic field are also shown. Note that the field intensity of the forward wave (shown in the solid line) is minimum at the ferrite slab, while the intensity of the reverse wave is maximum at the same point



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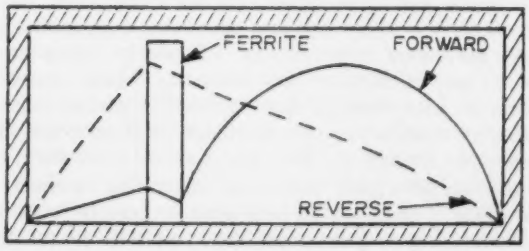


B

Figure 1-14. Electric fields in a waveguide.

(shown by the broken line). Now, when a coating of resistive material, such as graphite, is applied to one side of the ferrite slab, it absorbs most of the energy of the reverse wave. The forward wave is attenuated only slightly by the resistive coating because of its low field intensity at that point. The magnitude of the discrimination between the forward and reverse waves depends rather critically on such factors as the length and width of the ferrite slab; its location with respect to the guide wall; the strength of the applied magnetic field; and, particularly, the length, shape, and exact location of the resistive strip. In practice, representative losses introduced by the isolator of this type are about 0.2 dB in the forward direction of transmission and 30 to 35 dB in the reverse direction.

Because of the unidirectional properties of the ferrite isolator, you should be cautious when putting an isolator into a microwave line. The output and input connections are clearly marked on the isolator, and they should be inserted into the transmission line accordingly. Also, be careful not to strike the magnet about the isolator, since this can change the strength of the magnetic material. Finally, do not bring material or equipment that is affected by magnetic fields into close proximity with the magnetic field of the permanent magnet.

Exercises (609):

1. State briefly how a ferrite isolator attenuates the reverse wave, giving it the unidirectional properties.

2. What are some of the safety precautions you should observe when you are installing and working in close proximity to a ferrite isolator.

3. What is the function of a waveguide isolator in a line hookup?

1-3. Microwave Oscillators

Accurate RF signal generators are essential in most microwave test operations and laboratory measurements. These generators must provide RF energy, frequency, power, and modulation characteristics whose specific parameters may be easily determined. The heart of any of these generators is the basic oscillator which produces the microwave frequency. For this reason, our study of microwave principles would be incomplete without a discussion of some of the oscillators commonly found in microwave signal generators. Thus, we will discuss the klystron, traveling-wave tube amplifier, and backward wave oscillator, to include their construction and operating principles.

610. Specify the characteristics of the operation of the klyston, and state the advantage or disadvantage of using the reflex klystron over the double-cavity klystron.

Klystron Oscillator. Before we begin our discussion of the klystron, we will review some common electronic terms as they apply to the operation of the klystron.

Density modulation. In a triode tube, the number of electrons passing the control grid is controlled by the potential on the grid. The more positive the potential, the greater the number of electrons that will reach the plate element. Note that the bias on the control grid only controls the number, or density, not the velocity of the electrons.

Velocity modulation. The factor, which controls the velocity of the electrons as they pass from cathode to plate, is the difference in potential between those two elements. This principle is applicable in the following example. An electron beam is generated in an electron gun similar to a CRT. This beam is directed through an element called a cavity resonator. Since the beam contains all harmonics of the basic frequency, the cavity will be resonant at the harmonic to which it is tuned. The resonating electric field produced by the cavity will then interact with the electron beam. During one alternation of the resonant frequency, the electrons will be retarded by the energy from the cavity. During the opposite alternation, the beam will be accelerated. The beam velocity then, is determined by the potential on the cavity. Hence, the term "velocity modulation."

Construction and components. A klystron is a tube which has a positive grid and resonant cavities for tuned circuits. This tube is used to generate microwave frequencies. Because this tube causes the various electrons emitted to be accelerated or decelerated at different rates (thus varying their velocities), it is known as a velocity-modulated tube. There are two basic types of klystrons: double cavity and reflex.

Figure 1-15 shows the construction and essential components of a double-cavity klystron. In this klystron, the indirectly heated cathode emits electrons that are focused into a sharp beam by the control grid. The control grid is at a low-positive potential. The beam is then accelerated by a very high-positive DC potential on grids G_2 and G_3, which are very close together and are connected to a cavity resonator. Superimposed on this DC potential is an AC voltage that changes the acceleration of the various electrons differently. Those electrons that reach G_2 and G_3 at a time when the AC voltage is at zero are not affected and continue at their initial velocity. Electrons reaching the grids are either accelerated or decelerated in accordance with the polarity of the voltage applied to the grids (positive on the grids accelerates; negative on the grids decelerates).

Grids G_2 and G_3 are called buncher grids, because the electrons that accelerated differently by the action just described travel at different velocities through the drift space and will bunch at some point. When these bunches of electrons arrive at grids G_4 and G_5 and are decelerated, they deliver energy to the cavity resonator connected to these grids. Since the function of grids G_4 and G_5 is to absorb, or catch, the energy contained in these bunches, they are

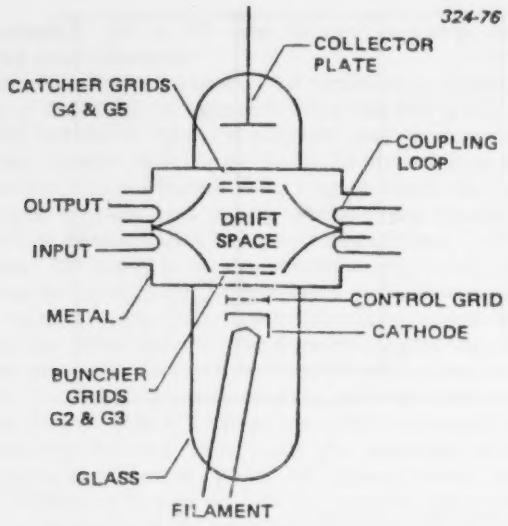


Figure 1-15. Two-cavity klystron.

called catcher grids. Electrons that continue through the catcher grids hit the collector plate and return to the cathode through an external circuit.

Operation. The bunching action occurring in the klystron is illustrated by the Applegate diagram shown in figure 1-16. In this diagram, the lines all start at the top of the diagram at the buncher grids; they represent the paths of the various electrons in their travel through the drift space. The AC-voltage waveshape at the top represents the AC component of the voltage on the buncher grids; the horizontal axis represents time. The lines are, therefore, tilted to the right in their passing from buncher to catcher grids. The difference in the slope of the various lines as they leave the buncher grids represents the different electron velocities. The different electron velocities are caused by the different accelerations imparted to these electrons by the AC component of the voltage on the buncher grids. Note that the electrons which arrive at the buncher grids between time T_0 and T_1 form a bunch at the catcher grids. There is only one bunch of electrons in each cycle; hence, the frequency of bunches arriving at the catcher grids is the same as the input frequency.

Drift space function. For the klystron to function most efficiently, the drift space should not be too long. If the distance between catcher and buncher grids is made too great, the bunches disappear or tend to merge, thus making the beam no longer usable. There is a certain spacing that gives best results with given DC and AC voltages. Since this spacing, called drift space, is fixed in a tube, the voltages must be accurately adjusted for the tube to function properly. Also, the resonant circuit of the catchers must be tuned to the correct frequency. The strength and phase of the oscillation must be such as to absorb maximum energy from the electron bunches.

Circuit operation. Figure 1-17 is a typical klystron oscillator circuit. Oscillations that are set up are maintained if the grid and plate voltages are in correct phase to cause positive regeneration. The time required for the electrons to travel through the drift space and bunch is an important consideration in this phase relationship. Since the drift space is fixed for a given tube, the DC voltage applied to the buncher grids (which may be considered to impart the average velocity to the bunch) is critical. A well-regulated voltage supply is essential for the proper operation of a klystron oscillator. Both the buncher and catcher cavities must be tuned to the same frequency. The output may be taken from either cavity through coupling loops by means of coaxial cables attached to either terminal.

Advantages versus disadvantages. The double-cavity type of klystron is capable of considerable power output; however, the difficulties encountered in the mechanical tuning of the two cavities make the reflex klystron more suitable for most uses.

Exercises (610):

1. Why is a klystron known as a velocity-modulated tube?

2. Which set of grids in a double-cavity klystron absorbs the energy from the electron bunches?

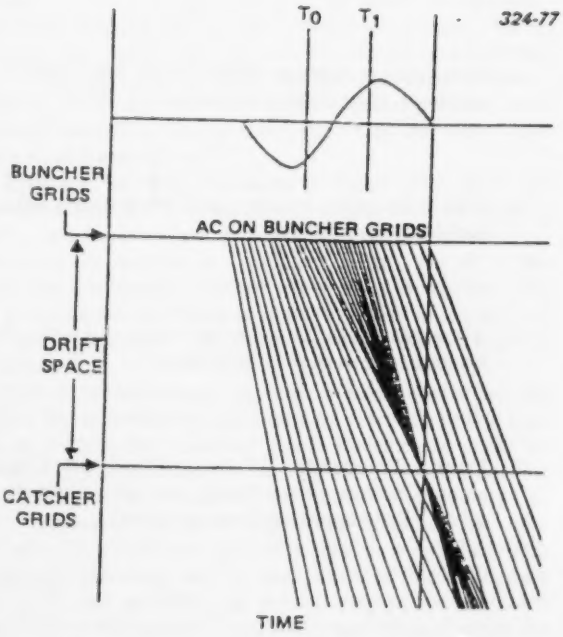


Figure 1-16. Two-cavity bunching action.

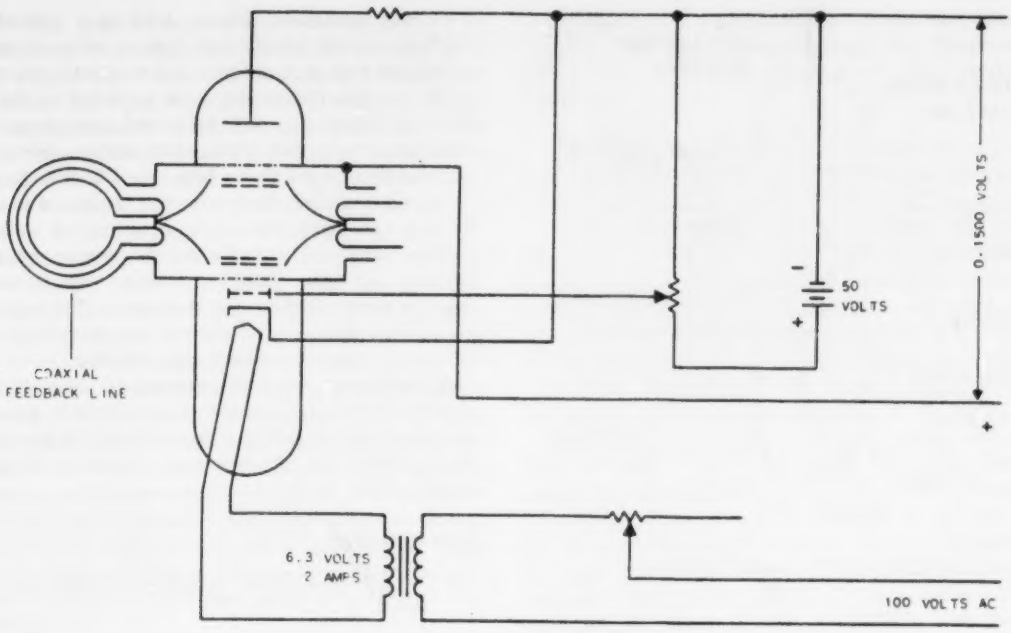


Figure 1-17. A complete klystron oscillator circuit.

3. State the relationship between the frequency of the electron bunches arriving at the catcher grids and the input frequency.

4. How can the klystron amplifier be converted to an oscillator, if it can be so converted?

5. Why is the reflex klystron used more widely than the double-cavity klystron?

6. What advantage is there in using a double-cavity klystron instead of a reflex klystron?

7. During the operation of the double-cavity klystron, some electrons of the bunch are not caught by the grids. What happens to these electrons?

611. Define the electronic tuning range and compare the plates of double cavity and reflex klystrons.

Reflex Klystron. The reflex klystron, which is used in many applications in the succeeding chapters, is a tube of the velocity-modulated type, which has only one cavity resonator.

Functions of the reflex klystron. The function of bunching and catching the electrons is performed by one cavity resonator of the re-entrant type built around grids. The distinguishing feature of the reflex klystron is an electrode known as a reflector, or repeller plate, which turns the bunches of electrons back to the cavity grids; hence the name, reflex klystron. The repeller plate does this because the voltage applied to it is negative with respect to the cathode. Figure 1-18 is a schematic representation of a typical reflex klystron oscillator circuit, showing the voltages applied to the electrodes and cavity grids. The tube consists of an indirectly heated cathode, a control grid which acts as a focusing electrode, a re-entrant cavity resonator built around two cavity grids, and a repeller plate. Because the potential on the cavity grids is 200 to 300 volts positive with respect to the cathode, the electrons emitted are attracted toward them. The control grid, which is slightly positive with respect to the cathode, focuses the electrons into a beam. After passing through the cavity, the beam of electrons enters the field between the cavity grids and the repeller plate. The repeller plate is maintained at approximately 100 volts negative with respect to the cathode. The beam is, therefore, decelerated by a field of

approximately 300 to 400 volts, brought to a stop, and repelled toward the cavity.

Operation. Let us see under what conditions oscillations set up in the cavity are sustained. Since this tube is of the velocity-modulated type, the electrons must be bunched and then brought back to the cavity in proper phase to deliver energy to it. Figure 1-19 is a diagram which, like the Applegate diagram used for the double-cavity klystron, shows how bunching takes place in a reflex klystron. In this diagram, the position of the resonator gap, which is between the cavity grids, is represented by one horizontal line; and the position of the repeller plate is represented by another line shown above it. The distance along the vertical axis represents the distance from the cavity grids toward the repeller plate, and the distance along the horizontal axis represents time. The AC voltage across the cavity grids is indicated by the sine wave along the horizontal axis. Electrons emitted by the cathode are attracted toward the cavity because of its high positive DC potential. Electrons arrive at the resonator gap when the AC voltage across it is positive, zero, or negative. An electron, a, arriving at the resonator gap at time t_1, when the AC voltage is zero, moves forward without a change in velocity; hence, it may be considered to be a reference electron. This electron travels into the drift space between the repeller plate and the resonator gap until it is decelerated sufficiently to be turned back toward the cavity. Another electron, b, arriving at the resonator gap at time t_0, when the AC voltage is positive, is accelerated and moves forward at a higher velocity than the reference electron; hence, electron b penetrates farther into the drift space before being decelerated sufficiently to be turned back than electron a did. A third electron, c, arriving at the resonator gap at time t_2, when the AC voltage is negative, is decelerated and moves forward at a lower velocity than the reference electron; hence, it does not penetrate as far into the drift space as the reference electron did before being decelerated sufficiently to be turned back.

Electron bunching. Although the three electrons singled out here travel different distances into the drift space and the velocities of the three are different, they are bunched during their travel; so they arrive back at the resonator gap together. Note that electron b, which starts before the reference electron a and travels at a greater velocity, also has greater transit time. Similarly, electron c, which passes through the gap later and travels with less velocity than the reference electron a, has a shorter transit time. The motion of these three electrons in the repeller space of a reflex klystron may be compared to that of three balls thrown upward against the force of gravity. If the three balls are thrown upward at equally spaced intervals of time with velocities that are large, medium, and small, respectively, the time intervals between them upon their return will be smaller than when they started out, because the first ball takes a longer time to return and the third takes a shorter time to return than the second does. Hence, they are more closely bunched in time on their return than they were when they were thrown upward.

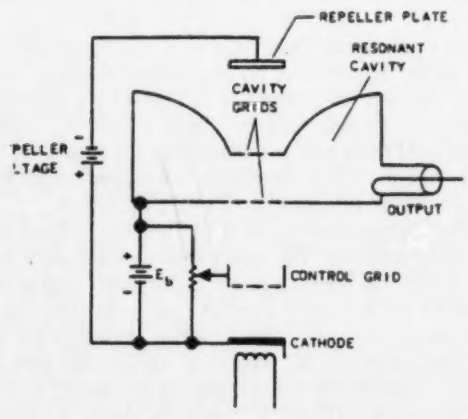


Figure 1-18. Circuit of a reflex klystron.

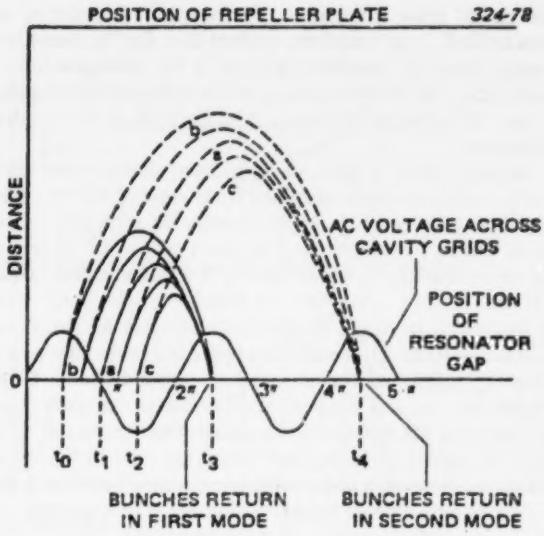


Figure 1-19. Bunching action of a reflex klystron.

Effects of electron bunching. In figure 1-19, all of the electrons that arrive at the resonator gap between times t_0 and t_1 are shown return to the grids in a bunch; but since electrons are emitted in a constant stream, not all of the electrons are bunched. Hence, electrons return to the grids in a stream which varies in intensity, with maximums of intensity (bunches) occurring once in each cycle of oscillation.

Effects of alternating current. We have seen that the reflex klystron velocity modulates the electrons so that they arrive back at the resonator gap in bunches. In order for these bunches of electrons to deliver energy to the resonator and thus sustain oscillation, they must be decelerated as they approach the grids. Since the electrons are now traveling in a direction opposite to that in which they were originally traveling, the AC component of the voltage on the grids has an effect on the velocity of the electrons opposite to that which it originally had. Hence, when the AC voltage across the cavity grids is positive, the bunches of electrons are decelerated; when the AC voltage across

the cavity grids is negative, the bunches of electrons are accelerated. It is, therefore, evident that, for the transfer of energy from the bunched electrons to the resonator to be a maximum, the bunches should arrive at the resonator gap at a time when the AC voltage across the grids is at a positive maximum.

Modes. Since a positive maximum occurs once each cycle, oscillations are sustained if the time of arrival of the bunches at the grids is made to coincide with any one of these positive maximums. Two such points are shown in figure 1-19 at time t_3 and at time t_4. A reflex klystron, which operates in such a way that the bunches of electrons return to the resonator in the shortest time possible for sustaining oscillation (time t_3), is said to be operating in the first mode. Time t_4 represents operation in the second mode. Other modes (not shown) are possible; the number of each mode increases as the repeller-space transit time increases. Note that, for operation in the first mode, the time in transit for reference electron b is the difference in time between t_3 and t_1. We discuss repeller modes further in the next section.

Exercises (611):

1. Compare the plates of double-cavity and reflex klystrons.

2. How may the electronic tuning range be defined?

3. What must occur if oscillations are to continue from a klystron oscillator?

4. Does the AC on the grid have the same effect on electron movement in the reflex klystron after bunching as it did on the outward movement of electrons? If not, how does it differ?

612. State how the repeller mode is affected by repeller voltage, and in what ways the frequency can be changed.

Comparison of Repeller Modes. Although the word "mode" is used to describe the field configurations found in waveguides and cavity resonators and is used also to describe the time in transit of electrons in a reflex klystron, there is no relationship between the two. To differentiate between them, the term "repeller mode," or "voltage mode," is often used for the reflex klystron, since the number of cycles of drift depends upon the difference in potential which exists between the repeller plate and the resonator gap. Variations in this difference in potential may be used to produce the various modes possible. Since the initial acceleration which the electrons receive as they travel from cathode to cavity grids is dependent upon the DC voltage that exists between the grids and the cathode, variations in this voltage not only affect the mode of operation but also affect the kinetic energy imparted to the electrons by the DC voltage. It is, therefore, found advisable in practice to keep the DC voltage applied to the cavity grids constant. A well-regulated power supply is used for this purpose. Thus, to obtain the various voltage modes, the repeller voltage is made variable. Its source is also a well-regulated power supply. For operation in the repeller mode in which the time in transit for the electrons is least, the repeller-plate voltage is made most negative. To make the time in transit greater for operation in other modes, the repeller-plate voltage is made less negative.

A comparison of both the power output and the frequency deviation of a typical reflex klystron, as its mode of operation is changed, reveals some interesting facts. Figure 1-20 illustrates the effect of varying the repeller-plate voltage of a reflex klystron on both these characteristics. Note that as the repeller voltage is progressively increased (made more negative), the oscillator goes in and out of oscillation several times. Thus, from figure 1-20,B, it is evident that no oscillations occur until the repeller voltage reaches the value V_1. The power output of the oscillator then increases with an increase in repeller voltage until a maximum is reached; and then, as the repeller voltage is further increased to the value V_2, the power output decreases until it is zero again. The oscillations do not start again until the value of the voltage on the repeller plate becomes V_3. From a value of V_3 to a value of V_4, the power output again varies from zero to a maximum and back to zero again. A period of no oscillations between values V_4 and V_5 of repeller voltage is followed by a recurrence of oscillations between voltage values V_5 and V_6. Again, the power goes from zero to a maximum and then back to zero. Thus, figure 1-20,B, represents the power output for each of three modes of operation of a reflex klystron.

More modes may occur if the repeller voltage is made still more negative. The maximums for each mode occur in each case if the bunches return to the cavity grid at the time when the AC voltage is a positive maximum (see fig. 1-19). Bunches of electrons may, however, return to the grids at any time when the AC voltage is positive and may give up energy. Oscillations are sustained if the energy given up by the bunches is sufficient to overcome losses. As the number of cycles of drift varies by an increasing amount from n +

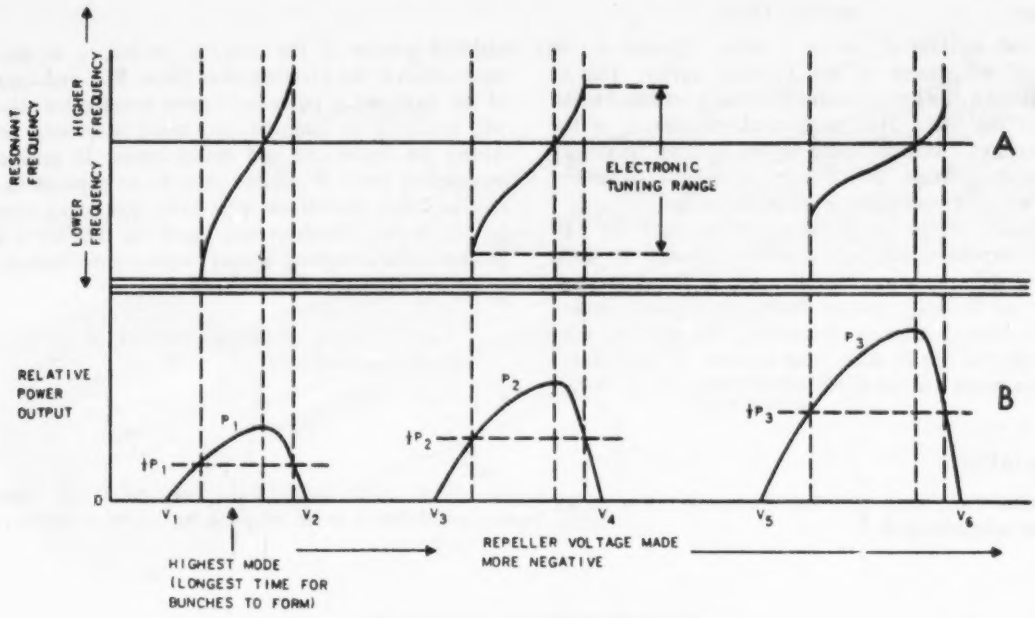


Figure 1-20. Effect of varying repeller voltage of a reflex klystron.

3/4 (where n = 0, 2, 3, 4,...), the power output falls off from a maximum. Thus, the variations of power output within each voltage mode shown in figure 1-20,B, are obtained.

Note that the overall power output of each mode becomes greater as the repeller voltage is made more negative. Thus, it is evident that the mode in which the electrons travel the least distance into the repeller space is the one in which the power output is greatest and that the mode in which the electrons travel the greatest distance into the repeller space yields the least power output. Figure 1-20,B, therefore, indicates that the highest mode is the one with the lowest power output; "highest," in this case, represents distance traveled into the repeller space. In addition to the usual losses that occur in an oscillatory circuit, the lower power output in the higher modes is caused by losses due to overbunching; that is, the bunching of electrons at a time before they reach the grids. Hence, by the time they reach the grids, they have begun to disperse, and the energy given up to the circuit is decreased. Overbunching occurs because the acceleration and deceleration of electrons become greater as the amplitude of the AC voltage across the grids increases. It is especially prone to affect the higher modes, where the bunches are formed more slowly. Hence, as the power output tends to increase, overbunching offsets this tendency by lowering the output. The power output of a reflex klystron in the higher modes is limited to an amplitude at which overbunching occurs.

Note that the maximum power for each of the modes shown in figure 1-20 (P_1, P_2, and P_3), although different in value, occurs at the resonant frequency of the cavity in each case. The reason for this is because the repeller voltage is such as to cause the bunches to return to the cavity grids at the instant the AC voltage across the grids is at a positive maximum. As you have already seen, oscillations occur (with lower power output) if the repeller voltage is made either lower or higher, and the repeller voltage causes the bunches to return to the grids either earlier or later than when a positive maximum occurs. If the bunches return earlier, because the repeller voltage is increased, the cavity resonates at a higher frequency than its resonant frequency. If the bunches return later, because the repeller voltage is decreased, the cavity resonates at a lower frequency than its resonant frequency. Since, in both cases, the cavity oscillates at a frequency which is off-resonance, the amplitude of the oscillations decreases by an amount which depends upon the Q (quality or merit factor) of the cavity and upon how far from resonance the frequency has deviated.

It is thus possible to tune a reflex klystron over a range of frequencies by varying the repeller-plate voltage. When this is done, the reflex klystron is said to be tuned electronically. The electronic tuning range of a reflex klystron is defined as that range of frequencies over which the power output exceeds 50 percent of the maximum power output. When dotted lines are drawn vertically from the half-power points of figure 1-20,B, to where they intersect the frequency curves for each mode shown in figure 1-20,A, the electronic tuning range for each mode is obtained. Note that the highest mode has the greatest electronic tuning range and that the tuning range decreases as lower modes are used. This is the reverse of the power output capabilities for each mode; that is, the highest mode has the least power output, and the power output increases as the lower modes are used.

A second method of tuning a reflex klystron is the mechanical adjustment of the klystron cavity. This is accomplished by means of a strut physically attached to the outside of the tube. The mechanical adjustment of the cavity provides a coarse tuning of the klystron frequency output in comparison to the fine control of frequency obtained when varying the repeller-plate voltage.

The choice of the mode of operation used for any particular purpose must be a compromise between the mode that gives greatest power and the one that has greatest tuning range. Usually, several modes are available which perform a desired function effectively. The designer then recommends the one he finds most suitable. In most cases, the repeller mode that has either 1¾ or 2¾ cycles of drift is chosen.

Exercises (612):

1. In what two ways may the frequency of a reflex klystron be changed?

2. Indicate the electronic tuning range of a reflex klystron in a given mode.

3. What effect will variations of repeller-plate voltage have on the output frequency of the klystron oscillator?

4. What is the relationship between frequency and power output as the repeller-plate voltage is made more negative after reaching oscillation?

5. Why does a lower mode of operation have a higher power output than a higher mode?

613. Cite the advantages and disadvantages of amplitude modulation.

Pulse Modulation. Because of the nature of the reflex klystron, amplitude modulation is impractical. Any change in voltage on the repeller will result in a change in the frequency of the output. If the electron beam voltage is varied, the velocity of the electrons will change, resulting again in frequency variation. Therefore, only frequency modulation is possible in the reflex klystron; amplitude modulation results in unwanted frequency variations.

Pulse modulation can be achieved quite simply by turning the oscillations of the klystron on and off. The most common method of pulse, or square wave, modulating the klystron is to modulate the repeller voltage. If the repeller voltage is varied rapidly between the repeller mode regions and the center of the repeller modes, a simple pulse modulation of the klystron takes place. Rise and decay time of the modulating pulse is of great importance, since this will result in an inherent, unwanted frequency variation during the finite rise and decay times. In practice, the modulating pulse is clipped prior to its application to the repeller. This assures the fastest rise and decay times with no overshoot. Overshoot may cause the repeller to shift to another mode, resulting in dual frequency oscillation.

Exercises (613):

1. Why is direct amplitude modulation of the reflex klystron undesirable?

2. What effect would slow rise and decay times of a modulating pulse have on the output frequency of the klystron?

3. How do overshoots on the modulating pulse affect the output frequency of the klystron?

614. Specify the function of the magnet surrounding the helix; identify the element receiving the input signal; and specify how amplification is achieved in the TWT.

Traveling-Wave Tube Amplifier. The traveling-wave tube (TWT) amplifier is not, in the strictest sense, an oscillator, since it requires an external source of microwave energy for operation. However, it is commonly used and referred to as a signal source, and is, therefore, included in this discussion.

The TWT has many uses due to its high gain and output, linear amplification characteristics, and very wide bandwidth. Since the TWT does not require tuning, it is easy to operate. In narrow bandwidth application, the TWT allows shifting of the band in question over a wide range of frequencies and maintaining linear response without changing the basic circuitry. It may also be used as a stable microwave amplifier using the output of a low-power klystron as the input source.

Figure 1-21 shows the elements of the TWT's construction. Figure 1-22 demonstrates the amplification process within the TWT during operation. Refer to these figures during the following discussion.

The basic TWT consists of an electron gun that projects a focused electron beam through a helically wound coil to a collector electrode, as shown in figure 1-21. The focused electrons are held in a pin-like beam through the center of the helix by a powerful magnetic field around the full length of the tube. The magnetic field can be obtained through an electromagnet, a permanent magnet, or a periodic permanent magnet (PPM), as in later models. The magnets provide the focusing element.

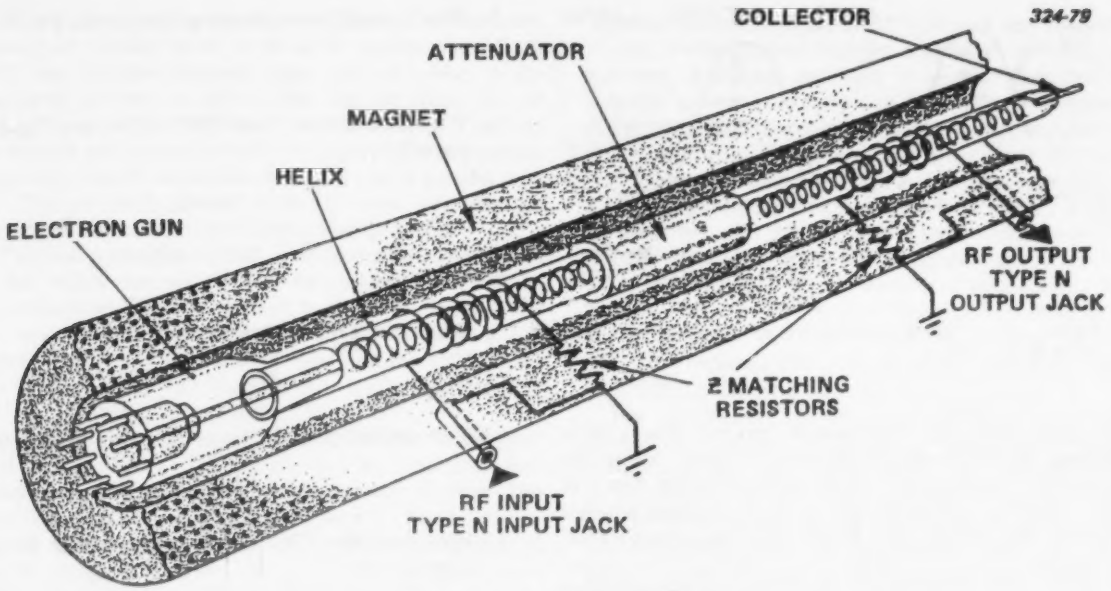


Figure 1-21. Traveling-wave tube.

An electron beam is produced by applying the operating voltages to the tube elements. The beam is focused by the solenoid (magnet) to a pin-like beam, through the center of the helix, to the collector element. A CW, RF signal is applied to the type "N" connector and coupled to the helix. The effect of the CW signal on the electron beam is a bunching of the beam's electrons, very similar to that which takes place in the klystron. The bunching action lags slightly behind the alternations of the CW signal. As the electrons bunch, their electric fields interact with the helix signal to reinforce the bunching action, and amplification of the signal begins. The newly formed bunches add voltage to the CW signal, which intensifies the bunching action, and so on. Figure 1-23 illustrates the relationship between the CW helix signal and the bunching action. Amplification continues, the velocity of the electrons increases, and the electron bunches are pulled more nearly in phase with the CW signal on the phase/in-phase/n helix. When the two electric fields are exactly in-phase, their additive effect is a resultant maximum amplification.

Attenuators placed near the center of the helix reduce any waves traveling on the helix to nearly zero, thus eliminating undesired signals, such as reflected waves caused by mismatch, from returning to the load. The attenuators do not affect the electron beam, and the previously formed bunches pass through unreduced. These bunches emerge from the attenuators, and their accompanying electric fields induce a new CW signal onto the helix, a signal exactly in-phase with, and of the same frequency as, the original input RF energy. The induced helix voltage builds up an electric field of its own, aiding that of the electron bunches,

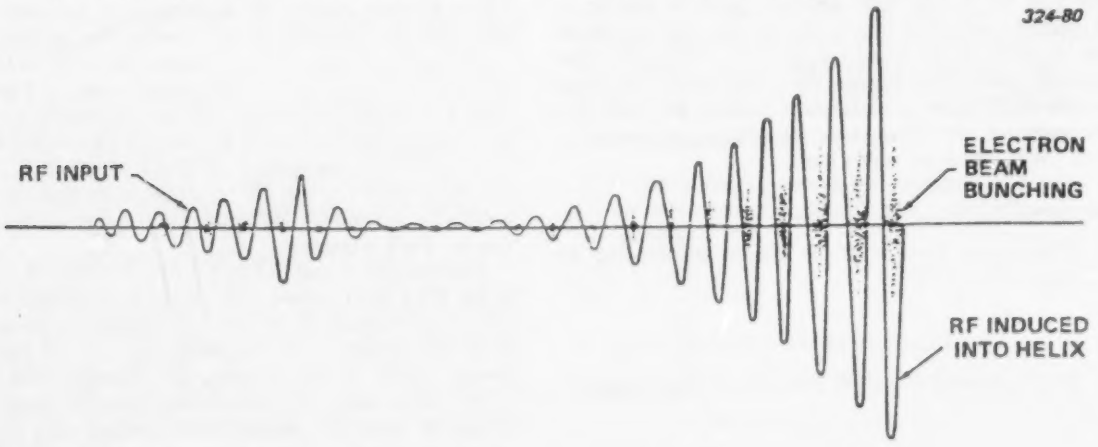


Figure 1-22. Amplification process in the TWT.

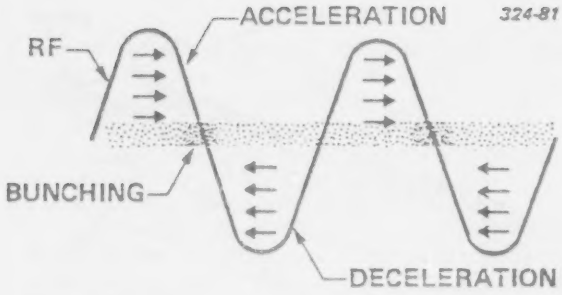


Figure 1-23. Velocity modulation of electrons by helix wave in the TWT.

beginning anew the amplification process. For a short distance, electron bunch velocity is reduced due to the extraction of energy by the helix in forming the new CW signal. As the increasing velocity of the electron bunches pulls the two signals more nearly in-phase, amplification increases.

At the point of the desired amplification, the amplified CW signal is coupled from the helix to the output type "N" connector. The output signal is a "new" CW signal whose energy is wholly supplied by the electron beam, the original signal having been eliminated by the attenuators near the center of the helix.

The traveling-wave tube amplifier is particularly suitable for use as the power amplifier of an amplitude-modulated master oscillator power amplifier (MOPA) system. This feature allows applications far beyond those possible using the reflex klystron, since the klystron cannot be directly modulated. The output of the TWT can be modulated with a sine-wave, pulse, or pulse train, without starting delays and jitter which are present when the oscillator is directly modulated.

Amplitude modulation is accomplished by varying the electron beam current while a CW signal is being amplified by the TWT. This current may be varied by changing the potential on any of the tube's elements (electrodes), including the modulation grid (not shown on fig. 1-21). This grid is in the tube envelope and is similar in construction and placement to the control grid in a triode tube. A disadvantage of grid modulation, however, is that amplitude modulated signals are accompanied by phase modulation. If phase modulation is desired, this method is quite effective due to the phase modulation characteristics of the TWT, which are nearly linear.

Exercises (614):

1. What is the function of the magnet surrounding the helix in the TWT?

2. Which element of the TWT receives the input signal?

3. How is amplification accomplished in the TWT?

4. Why is the output of the TWT said to be a "new" RF signal?

5. Why is the TWT not truly a signal source?

6. How are the electrons formed into a pin-like beam?

7. How does the TWT output compare with the input signal?

615. List TWT protection circuits, and specify their operation.

TWT Protection Circuits. The protection circuits for a TWT amplifier can be divided into three groups. These provide warmup time, overcurrent, and overtemperature protection for the TWT amplifier tube. The amplifier illustrated in foldout 1 (printed at the end of this volume) represents typical TWT amplifier circuitry. Refer to this foldout as we discuss the protection circuits. Keep in mind that the circuits we present can be connected in different ways to produce the same results.

Time delay circuit. A time delay circuit is used to allow the TWT heater to operate without applying the operating bias to the TWT. K3 (FO 1) is a 1-minute time delay relay whose contacts control the application of 115-volt power ultimately to K2 whose contacts control the application of operating bias to the TWT. Assuming S1 to be in the ON position, the ready lamp (DS2) would come on 2 minutes after S1 is turned to the ON position. Switching S1 to the RF position applies power to K2 through the contacts of K1, TS1, and CR18, energizing K2 (the contacts of K2 are in the anode circuit of the TWT). At the same time the ready lamp goes out and the HV lamp (DS3) comes on indicating that the TWT is operating.

Overcurrent circuit. Relay K1 (the overcurrent relay) is in the TWT helix current path. When an excessive amount of current is drawn by the TWT, K1 energizes. Its contacts break the circuit of K2, removing the 115-volt operating power, which in turn removes the operating bias of the TWT. At the same time, the overload indicator lamp (DS4) comes on. Relay K1 remains in this position until the cause of the overload has been removed and the manual reset button has been pushed in.

As we have just stated, K1 energizes if an excessive amount of current exists in the helix current path. Each TWT has its own characteristics, one of which is the maximum amount of current that may be drawn by the helix. The amount of current that may be drawn is marked on the tube and is used to set K1 during the tube installation procedure. Notice on foldout 1 that R36 is in parallel with K1. This resistor is adjusted so that K1 energizes when the maximum current allowable is drawn by the helix.

Thermal protection circuit. The third area of protection is that which concerns the overheating of the TWT. A thermal sensor (TS1) is attached to the TWT. If the TWT overheats, TS1 opens removing the 115 volts from K2, thereby removing the operating bias from the TWT. After the TWT cools down, power is automatically restored to K2, reapplying the operating bias to the TWT.

It should be noted that in each case K2 was deenergized to disable the TWT. The circuits that we have illustrated could have been accomplished in a number of ways. The time delay circuit could consist of an RC circuit with the amount of delay being dependent on the time constant of the RC circuit. Likewise, the power supplies could have independent circuits and be disabled to stop TWT operation when overload or overtemperature conditions exist.

Exercises (615):

1. List the TWT protection circuits and briefly explain their operation.

2. How is the 115 volts restored after having been removed by overcurrent and overtemperature conditions?

616. State the purpose of TWT amplifier power supply components.

TWT Power Supplies. There are four power supplies illustrated on foldout 1. Two of these provide power for the TWT—the regulated high voltage for the helix and the unregulated high voltage for the TWT collector. The other two are used to obtain the appropriate control voltage for the regulated high voltage supply.

High voltage unregulated supply. This power supply is a conventional full-wave bridge rectifier circuit using a pi-type filter circuit. Its output is used as the collector potential of the TWT. A study of the bridge rectifier circuit reveals capacitor (C16 through C19) in parallel with the bridge diodes. These capacitors provide for suppression of transients in the rectifier circuit. The output of this supply is about 1,400 volts.

High voltage regulated supply. This supply provides the regulated potential to the helix. As with the unregulated supply, a conventional rectifier and bridge circuit is used, however, a voltage regulator is used to hold the helix potential constant. A sample of the output is applied to a differential amplifier circuit where it is compared to a reference voltage established by a zener diode. The output of the differential amplifiers is amplified and coupled to the high voltage regulator tube. This voltage, which is applied to the control grid of the regulator tube, varies current flow through the tube, thereby regulating the voltage applied to the helix. Keep in mind that the path of helix current flow is from the negative side of the bridge rectifier circuit to R30, the cathode of the TWT, the helix, ground, K1–R36, M1–R37, regulator tube, and finally to the positive side of the bridge rectifier-filter circuit.

The +150-volt supply. The output of this supply provides a regulated +150 VDC to the screen of the helix voltage regulator tube. Regulation of the 150-volt output is accomplished through use of a zener diode. In addition to providing the screen voltage, the regulated 150-volt output is used to operate an elapsed time meter. This meter records the power-on time of the TWT, which has a definite time usefulness.

The −40-volt supply. The −40-volt output is obtained from a bridge rectifier circuit whose output is filtered by a pi-type filter. The output is regulated to approximately −40 volts by a pass transistor (Q1). Changes in voltage are sensed by the base of control amplifier Q2. The emitter of Q2 is held to a fixed reference voltage by zener diode CR16 so any changes on the base are felt by the collector of Q2 and accordingly by the base of Q1. Since the base of Q2 is tied to a fixed point between R17 and R18, the output voltage of power supply, while being held to approximately −40 volts, is not adjustable.

The −40-volt output is used to power the differential amplifier circuit whose output controls the helix high voltage regulator. The −40 volts is applied across the R24–R25–CR17 circuit to establish a variable regulated voltage to be used as one of the inputs to the differential amplifier. The second input to the differential amplifier is output of the voltage divider made up of R4 through R12, R31, and R14. The difference output is directly coupled to amplifiers Q7 and Q8 with the resultant output control voltage being developed across R29. The control voltage is then applied to the high voltage regulator tube V1 to provide the necessary regulation of the helix voltage.

Exercises (616):

1. What is the purpose of the capacitors in parallel with the rectifiers of the TWT helix and collector power supplies?

2. How is the helix voltage regulated?

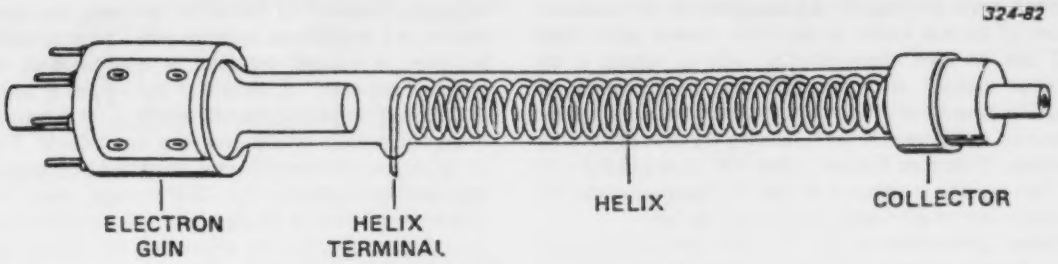


Figure 1–24. Backward-wave oscillator tube.

617. State how the operating frequency of the BWO is established; compare the beam of the BWO and TWT; and indicate how the helix wave and electron bunches are related.

Backward-Wave Oscillator. The backward-wave oscillator (BWO) provides a flexible source of microwave energy that can be voltage tuned to produce a wide range of frequencies. The output frequency of the BWO is determined by a frequency-selective feedback and amplification process rather than by resonant circuits as used in conventional microwave oscillators. Figure 1-24 illustrates the construction of the backward-wave oscillator.

Structure. The backward-wave oscillator tube consists of an electron gun, a helix structure, and a collector at the far end of the helix. Physically, the BWO resembles the traveling-wave tube, although for comparable frequencies, it is larger in diameter and somewhat shorter in length. Another difference, not apparent from a visual inspection of the tube, is that the helical BWO uses a hollow electron beam with a strong concentration of the electrons near the helix. This hollow electron beam is focused along the length of the helix by a strong magnetic field supplied by an axial solenoid or magnet surrounding the tube.

The RF output of the BWO is a result of the interaction between the electron beam and the electric fields accompanying a microwave signal, present on the helix. The term "backward-wave oscillator" is quite appropriate for this tube, since the RF energy moves and builds up in a direction opposite to that of the electron beam and is coupled out at the gun end of the tube, via the helix terminal.

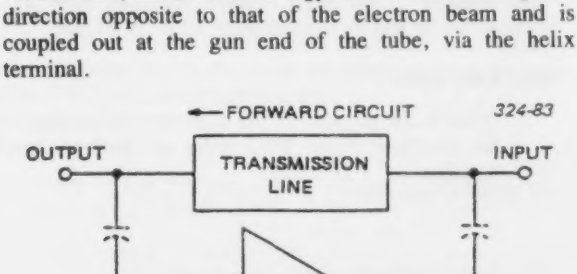


Figure 1-25. Typical feedback loop.

Basic theory of operation. The operation of the BW may best be explained in terms of a series of regenerat feedback loops. Each of these loops can function as amplifier of an oscillator, the phase shift in the loop be equal to one cycle. As shown in figure 1-25, each lo consists of a section of transmission line, a unidirectio amplifier, and two coupling capacitors. Positive feedba necessary for oscillation, will occur when the amplifier g overcomes the inherent loss of the transmission line. T frequency of oscillation is dependent upon the phase shif the amplifier, therefore, the frequency may be varied changing the phase delay of the amplifier.

Figure 1-26 illustrates a combination of these feedb loops, connected in a chain. In operation, the forw circuit consists of the sections of transmission line, electrical energy being propagated from input to outp right to left. The combined effect of the feedback loops wave traveling in the reverse direction, left to right. figure 1-27, a cross section of the BWO helix, the elect beam, and helix wave are shown. As the electron be passes through the tube, the strong axial field produced the magnet interacts with it and forms rotating fields ab the turns of the helix.

As shown in figure 1-27, the field rotation acceler and decelerates the beam alternately, the helix w becoming sinusoidal in shape. Note that the electric fi on the helix turns are maximum between the turns minimum when directly opposite the turns. This is beca no electric field can exist parallel to a conductor. The ef of the helix fields is to increase bunching of electrons in electron beam. The bunches, in turn, impart energy to helix fields, and amplification occurs, as in the TWT. result of these interactions is a concentration of electrons into a spiral about the hollow electron beam. average velocity of the electron beam is greater than tha the amplifier chain, so that the electron bunches advanced a quarter of a cycle as they approach the colle end of the gun; therefore, they encounter maxim decelerating effect and give up maximum energy to helix wave (fig. 1-28). The helix wave is coupled out of gun end of the tube and has a frequency determined so by the electron beam velocity, which is dependent upon phase delay of the feedback loops, a function of the cath to helix voltage of the tube.

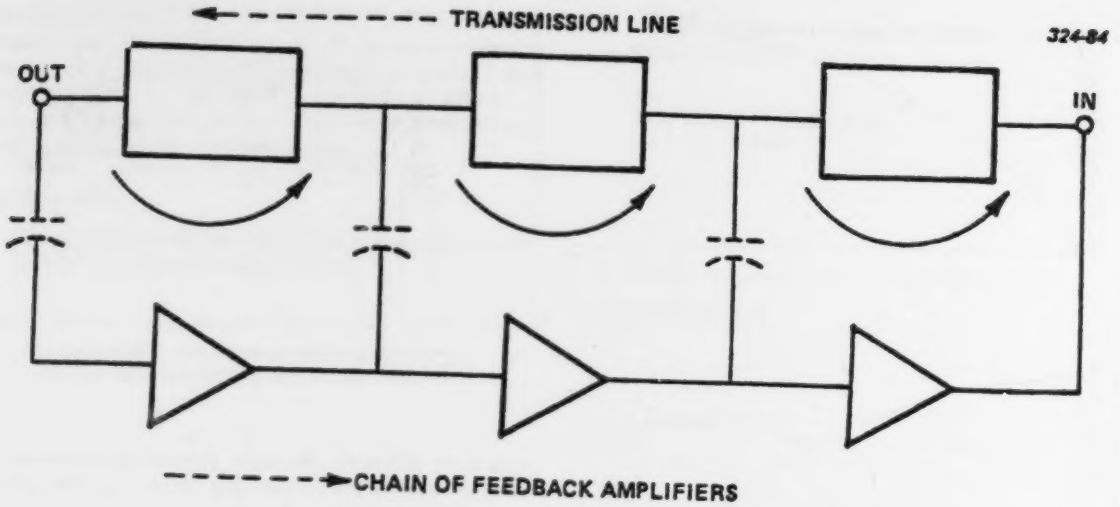


Figure 1-26. Typical chain of feedback loops.

The BWO can, therefore, be made to produce frequencies over a wide band by varying, within limits, the helix voltage. It can also be made to sweep a band of frequencies by applying a ramp or sawtooth voltage of proper amplitude to the helix.

Exercises (617):

1. How is the operating frequency of the BWO established?

2. What is the difference between the electron beam of the BWO and that of the TWT?

3. What feature of the BWO gives it its name?

4. How may the BWO be made to sweep a given band of frequencies?

5. What is the relationship between the helix wave and the electron bunches?

6. How can the frequency of the BWO be changed?

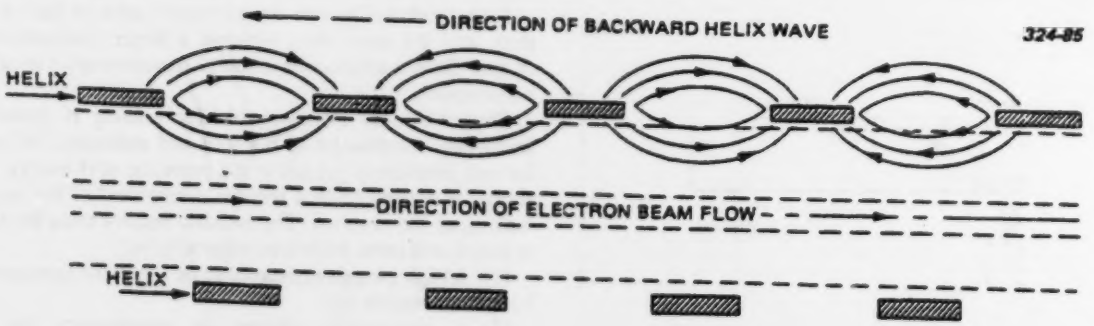
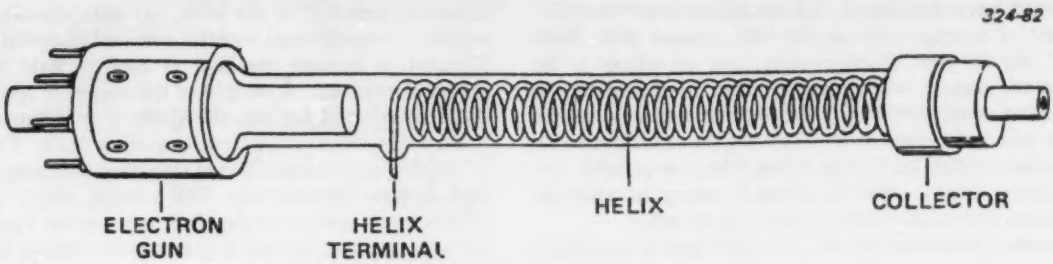


Figure 1-27. Cross section of helix, electron beam, and helix wave.



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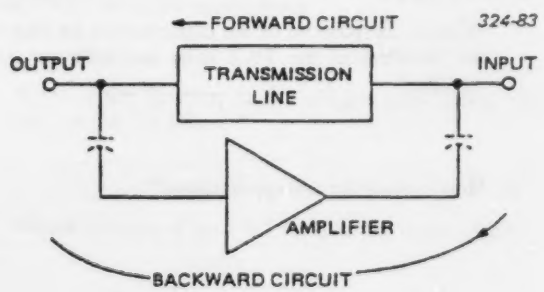

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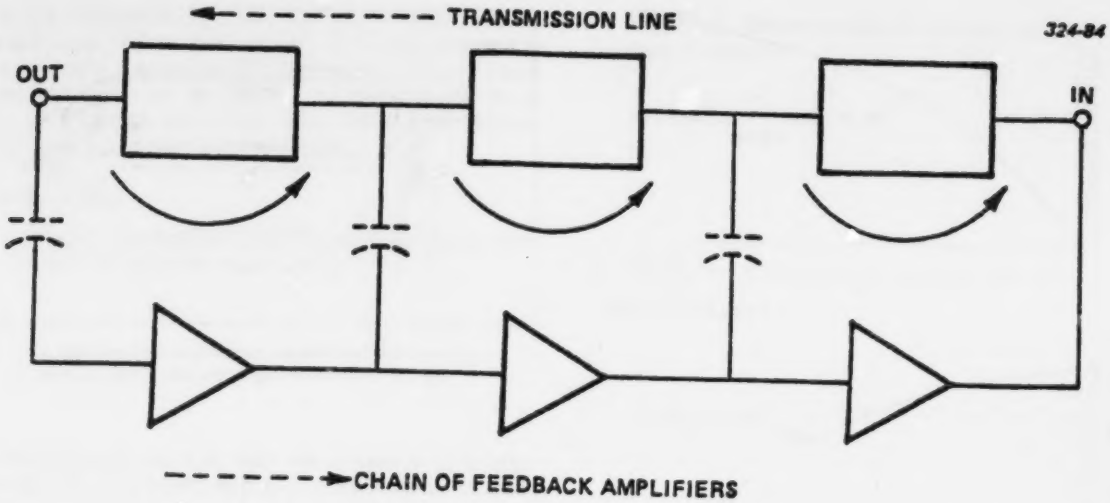

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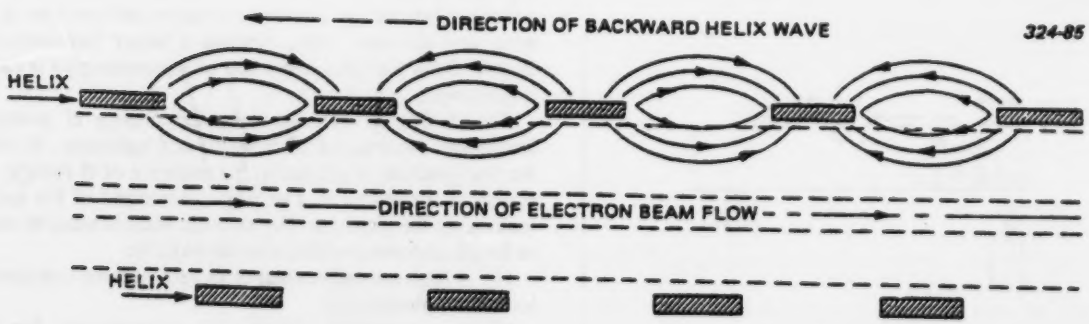


Figure 1-27. Cross section of helix, electron beam, and helix wave.

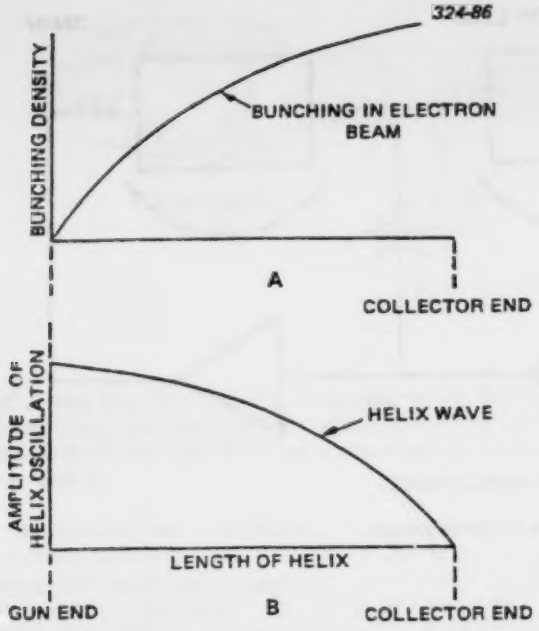


Figure 1-28. Relative amplitude of helix wave versus degree of electron bunching in the BWO.

618. State the operating principles of thermocouples and identify the materials used for construction.

Principles of Thermocouples. Thermocouples generate a voltage due to temperature differences along the thermocouples. As a simple example of the kind of physics involved, imagine a long metal rod that is heated at the left end as in figure 1-29. Because of the increased thermal agitation at the left end, many additional electrons become free from their parent atoms. The increased density of electrons at the left causes diffusion toward the right. There is also a force attempting to diffuse the positive ions to the right but the ions are locked into the metallic structure and cannot migrate. So far, this explanation has not depended on Coulomb forces. The migration of electrons toward the

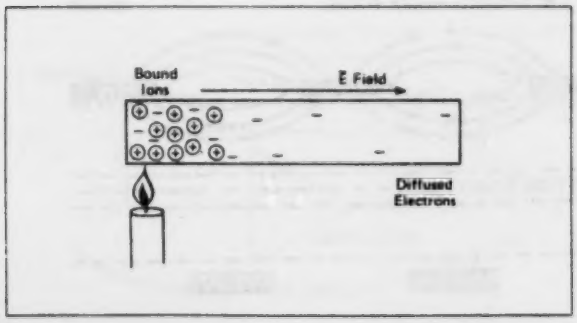


Figure 1-29. Heat at one end of a metal rod gives rise to an electric field.

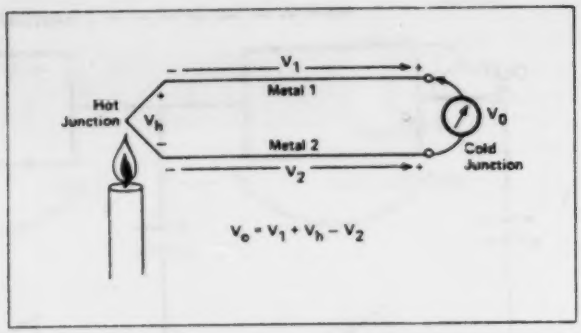


Figure 1-30. Total thermocouple output is the resultant of several thermoelectric voltages generated along the circuit.

right is by diffusion, the same physical phenomenon that tends to equalize the partial pressure of a gas throughout a room, for example.

Each electron that migrates to the right leaves behind a positive ion. That ion tends to attract the electron back to the left with a force given by Coulomb's law. The rod reaches equilibrium when the rightward force of diffusion is exactly balanced by the leftward force of Coulomb's law. The leftward force can be represented by an electric field pointing toward the right. The electric field, summed up along the length of the rod, gives rise to a voltage source, called the Thomson emf. This explanation is greatly simplified but it does indicate the principle.

The same principles apply at a junction of dissimilar metals, where different free electron densities in the two metals give rise to diffusion and an emf. The name of this phenomenon is the Peltier effect.

A thermocouple is usually a loop or circuit of two different materials as shown in figure 1-30. One junction of the materials is exposed to the heat, the other is not. The complete loop is broken once to insert a sensitive voltmeter for measuring the net emf. The thermocouple loop uses both the Thomson emf and the Peltier emf to produce the net thermoelectric voltage. The total effect is also known as the Seeback emf.

Sometimes, many pairs of junctions or thermocouples are connected in series so that the first junction of each pair is exposed to heat and the second is not. In this way the net voltage produced by one thermocouple adds to that of the next, and the next, etc., yielding a larger thermoelectric output. Such a series connection of thermocouples is called a thermopile.

The traditional thermocouple for sensing rf power is frequently constructed of bismuth and antimony. In order for one junction to get hot in the presence of rf energy, the energy is dissipated in a resistor constructed of the metals making up the junction. The metallic resistor must be small in length and cross section in order to have:

(1) A high enough resistance to be a suitable termination for a transmission line.

(2) A measurable change in temperature for the minimum power to be measured.

(3) A uniform frequency response.

Thin-film techniques are normally used to build metallic thermocouples. These small metallic thermocouples tend to have parasitic reactances and low burnout levels. Large thermopiles tend to be plagued by reactive effects at microwave frequencies because device dimensions become significant with respect to a wavelength.

Exercises (618):

1. Voltages generated by a thermocouple are due to what differences along the thermocouple?

2. In general, thermocouples are constructed from what type of materials?

3. What is the phenomenon of the Peltier effect?

Microwave Measurements

CALIBRATION and repair of equipment related to microwave measurements are responsibilities of the PME technician. As the inventory continues to increase in the number of highly sophisticated systems utilizing microwave frequencies, the need for greater accuracies in microwave measurements and maintenance procedures also increases. During our discussion of microwave measurements we will examine some of the aspects of equipment operating frequencies, frequency measuring devices, and standing-wave measuring equipment.

2-1. Electromagnetic Spectrum

Over the years, advancements in electronics have brought about utilization of greater portions of the frequency spectrum. In the first section of this chapter we will identify general characteristic relationships of subjects you have studied earlier. This includes optical principles of Volume 2, vibration principles of Volume 2, radioactive sources of Volume 3, as well as any of your studies of the 5-level CDC.

619. Specify frequency spectrum units of measure and applications and how they relate to each other.

Frequency Spectrum. The frequency spectrum covers the entire range of electromagnetic wave radiations from below the audible range at the low end, to cosmic rays at the high end. Figure 2-1 illustrates a partial breakdown of the application or assignment of the spectrum. Note that as the frequency (Hz) of the spectrum increases, the wavelength (angstrom units) of the wave decreases.

Radiation. The upper end of the spectrum consists of those waves which emanate from medical equipment (X-rays) and those from outer space called cosmic rays. Also included are gamma radiations from radioactive sources such as cesium 137. The wavelength of these waves is usually expressed in angstrom units.

Light. The next section of the spectrum covers light waves. Essentially, this section is divided into three parts—infrared light, visible light, and ultraviolet light. The unit of measure for the length of light waves is usually either the angstrom or the millimicron, both of which are based on the centimeter.

Hertzan waves. The third section of the spectrum is comprised of the balance of the spectrum. The unit of measure used indicates the number of oscillations per second rather than the wavelength of one oscillation. Within this section we have the means of most of our communications. Segments of this section and some of their uses are:

Sonic	20 Hz to 20 kHz	Human voice, musical notes, electrical power transmission.
Ultrasonic	20 kHz to 30 kHz	Underwater detection systems, cleaning devices.
AM Radio	550 kHz to 1.6 MHz	General commercial amplitude modulated (AM) broadcast band.
FM Radio	88 MHz to 108 MHz	General commercial frequency modulated (FM) broadcast band.
Radar	60 MHz to 30 GHz	Above water detection and navigation systems.

As you study figure 2-1, notice the letter designation of the various groups within the third segment that we discussed. These designations, such as ELF, MF, or VHF, are based on the following:

E	Extremely
F	Frequency
H	High
L	Low
M	Middle
S	Super
V	Very
U	Ultra

Exercises (619):

1. What is the unit of measure for X-rays?

2. How does the wavelength of gamma rays compare to the wavelength of infrared light?

3. Define the letter combination "SHF" as it relates to the electromagnetic wave spectrum.

4. What relationship exists between the angstrom, the millimicron, and the centimeter?

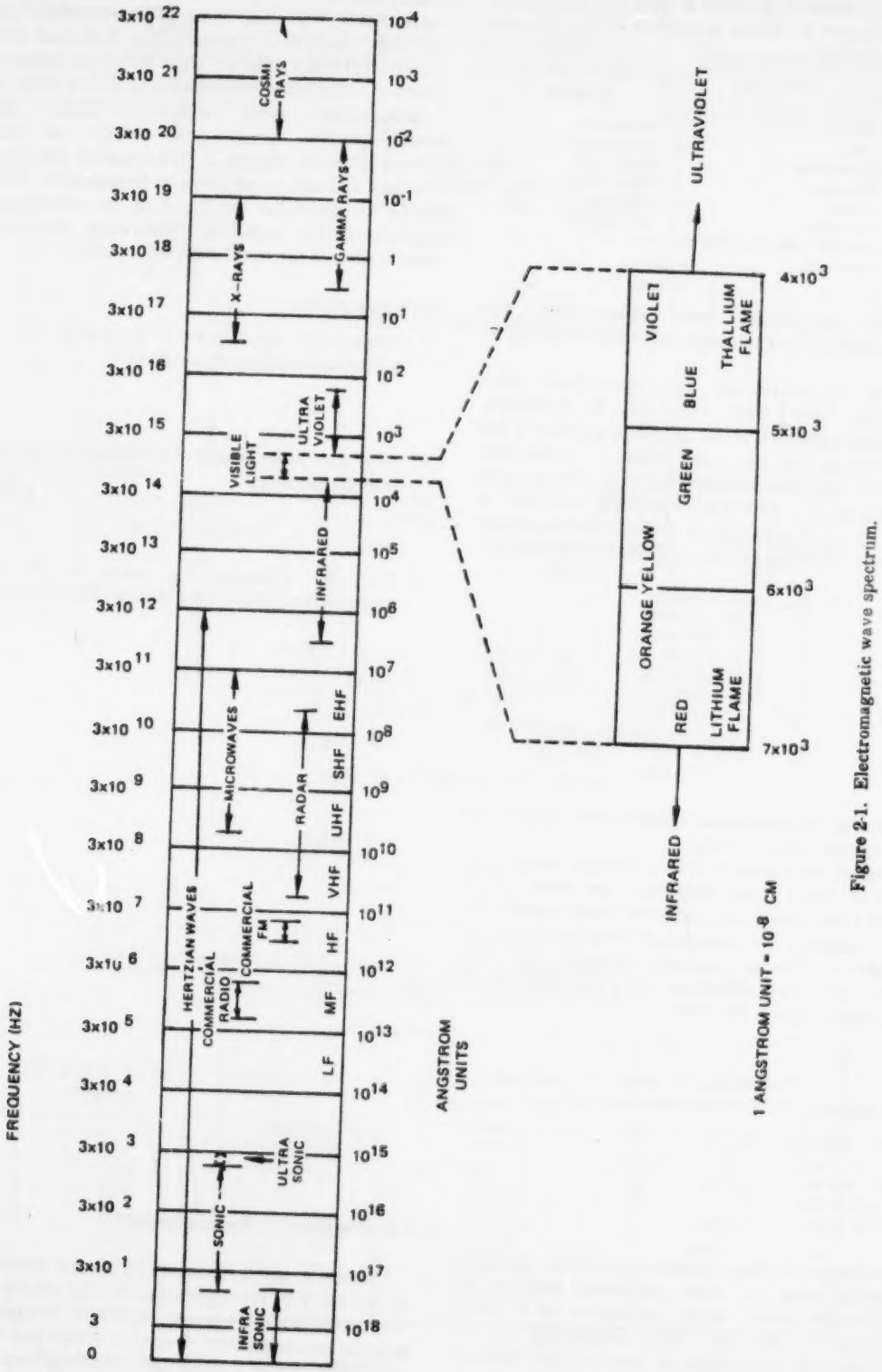


Figure 2-1. Electromagnetic wave spectrum.

5. Match each item in column A with the appropriate item in Column B. Items in column B may be used more than once:

Column A	*Column B*
____ (1) Sonic.	a. Gamma ray.
____ (2) Light.	b. Radar wave.
____ (3) Commercial.	c. Black light.
____ (4) Microwave.	d. Human voice.
____ (5) Shortest wavelength.	e. 1500 kHz.
____ (6) Longest wavelength.	f. 6K angstroms.

620. Identify microwave band designators and equipment crossband interchangeability characteristics.

Microwaves. The microwave region encompasses three of these groups—UHF, SHF, and EHF. By definition, microwave frequencies fall in the spectrum between 1 and 300 GHz. Because of the wide range of frequencies involved and the characteristics of microwave energy, most microwave equipment and accessories are designed to operate over a small segment of the microwave range. These segments, called bands, are identified as follows:

S	2.6 - 3.95 GHz
G	3.95 - 5.85 GHz
C	4.7 - 7.05 GHz
J	5.3 - 8.2 GHz
H	7.05 - 10.0 GHz
X	8.2 - 12.4 GHz
M	10.0 - 15.0 GHz
	P12.4 - 18.0 GHz
K	18.0 - 26.5 GHz
R	26.5 - 40.0 GHz

The upper end of the microwave band between 40 and 300 GHz is still in a development stage.

Depending on the manufacturer, equipment designed to operate within these bands may carry the same model number with a band prefix or a different model number for each band. Consider, for example, selfreading frequency meters made by Hewlett Packard Company and PRD Electronics, Inc. The following is a comparison of equipment model numbers by band:

Band	Frequency	Hewlett Packard	PRD Electronics
G	3.95 - 5.85 GHz	G532A	532
J	5.3 - 8.2 GHz	J532A	533
H	7.05 - 10.0 GHz	H532A	534
X	8.2 - 12.4 GHz	X532A	535
P	12.4 - 18.0 GHz	P532A	536

The significance of these designations shows up during the equipment setup for some procedure such as the maximum-leveled power output calibration of a sweep oscillator plug-in unit (fig. 2-2). Depending on the frequency involved, three bands of operation are reflected by the J, P, and X prefixes on the model numbers of the adapters, directional couplers, attenuators, detectors, and thermistor mounts.

By comparison to the use of prefixes, a typical frequency measurement (fig. 2-3) using PRD electronics equipment lists only component nomenclature. You must extract the component model numbers for a particular frequency from a table of compatible components, as shown in the figure.

Components from different bands are not interchangeable. From your study of waveguide characteristics in chapter 1, it is apparent that wavelength becomes critical at microwave frequencies. Waveguide design characteristics are based on the wavelength to be transmitted—the higher the frequency, the shorter the wavelength and the smaller the waveguide.

Exercises (620):

1. What is the significance of the prefix "H" on some microwave equipment models?

2. Why aren't components for different microwave bands interchangeable?

3. List the identifier for each of the following frequencies. (There may be more than one identifier.)

   a. 2.8 GHz.

   b. 5 GHz.

   c. 8 GHz.

   d. 10 GHz.

   e. 14 GHz.

   f. 20 GHz.

2-2. Frequency Measurement

Frequency can be measured by several methods that var the accuracy of the measurement. The electronic counter when used with a transfer oscillator, is capable of ver accurate measurements. A second device that you may us with good accuracy is the direct reading frequency meter In the following discussion, we describe each metho starting with the electronic counter method.

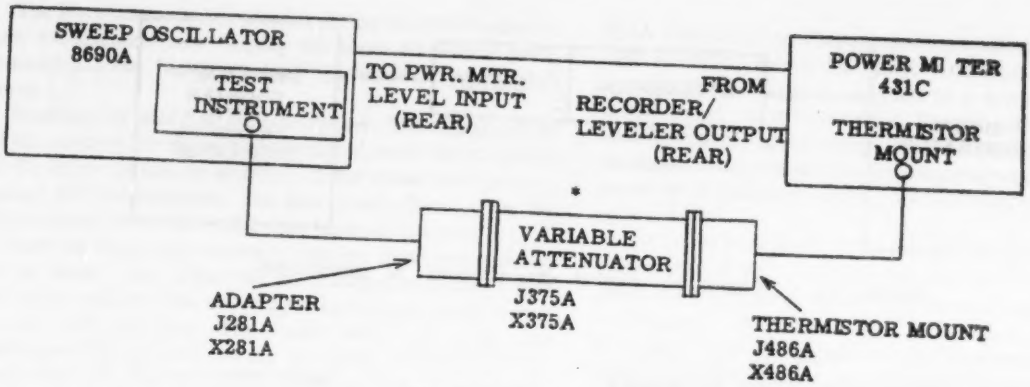


FIGURE 1A (Model 8694 series)

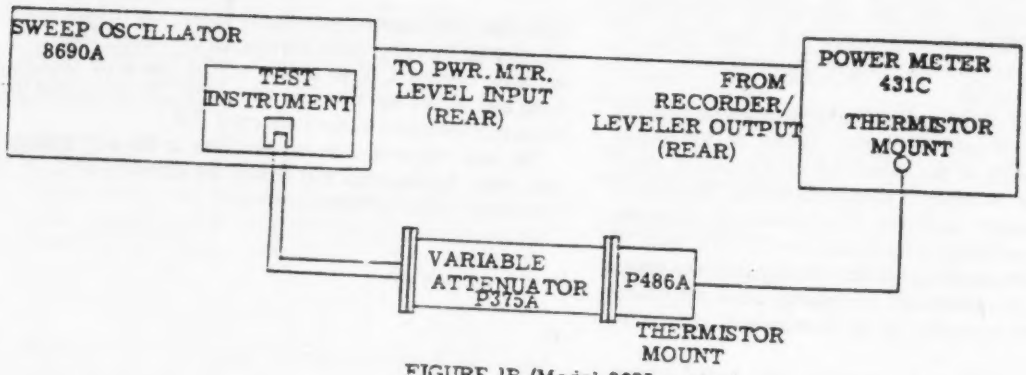


FIGURE 1B (Model 8695 series)

Change 3

Figure 2-2. TO extract calibration setup.

TABLE 2

SELECTION OF LEVEL SET ATTENUATOR AND DETECTOR
FOR FREQUENCY MEASUREMENT SETUP

Frequency Meter Type No.	Frequency Range	PRD Level Set Attenuator Type No.	PRD Detector Mount Type No.
532	3.95 - 5.85	162-A	*
533	5.85 - 8.2	156-A	*
534	7 - 10	160-B	*
535	8.2 - 12.4	159-A	610
536	12.4 - 18.0	158-A	6604
537-F1	18.0 - 26.5	155-F1	621-AF1
538-F1	26.5 - 4.0	157-F1	*

*Use suitable commercial equipment

Figure 2-3. TO extract frequency measurement.

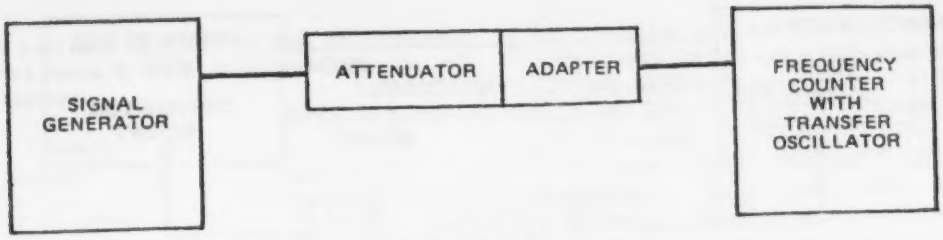


Figure 2-4. Frequency counter measurement of microwaves.

621. State characteristics and conditions for making frequency measurements with an electronic counter.

Electronic Counter Method. Frequencies up to 18 GHz can be accurately measured with the HP–5245L electronic counter with the HP–5257A transfer oscillator plug-in unit. Using this equipment with the appropriate connectors, adapters, and attenuators as required (fig. 2-4), you can measure continuous-wave, frequency-modulated, and pulse-modulated signals.

The selection of the equipment items depends on both the frequency involved and the power output of the signal source. Accordingly, if the signal source operates in the P band, an adapter is required to accommodate the coaxial input to the transfer oscillator. The maximum allowable power input to the transfer oscillator is +10 dBm for CW carriers and 2 volts peak to peak for any signal. If the power output exceeds the allowable maximum, or if any doubt exists as to signal strength, use an attenuator to reduce the power input.

Making pulsed RF measurements. The initial control settings (fig. 2-5) for making a pulsed RF measurement are as follows:

Counter Controls

Sample	Just out of power off.
Sensitivity	To plug-in.
Time base	To 0.1 ms.
Function	To frequency.

Plug-in Controls

Mode	Pulsed RF.
Range	Correct range for input signal.
Level adj	Fully CCW.
N switches	To 001.

Now, tune the frequency control to obtain a zero beat which is indicated by a maximum reading on the meter. Then, turn the level control CW to obtain a 9/10 full-scale reading. Read and record the counters as f_1. (NOTE: Disregard the frequency indicated by the frequency dial.)

The next step is to tune the oscillator to the next adjacent zero beat. Again, read and record the counters as f_2. N is calculated using the formula:

$N = f_1 / (f_2 - f_1)$
if f_2 is greater than f_1

or

$h = f_1 / (f_1 - f_2)$
if f_1 is greater than f_2)

Simply stated: The first frequency divided by the difference of the two frequencies is the harmonic number (N) of the second frequency. (NOTE: Slide rule accuracy in the calculation of N is adequate for counter operation.)

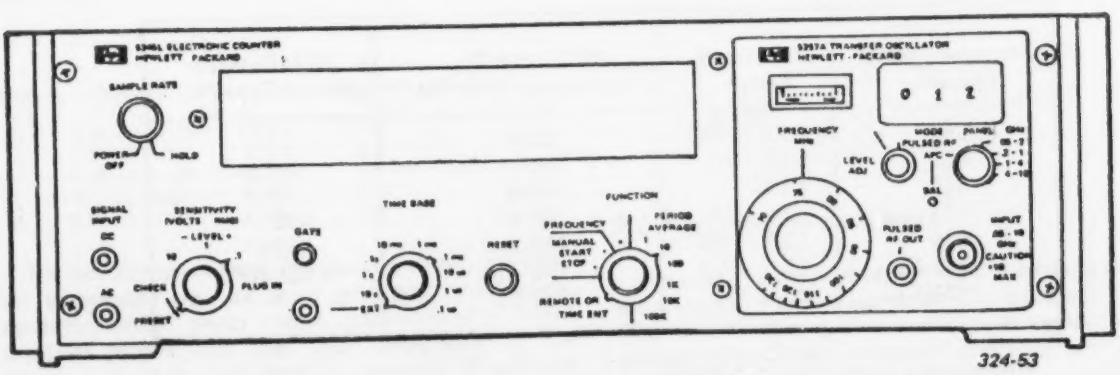


Figure 2-5. 5245L counter with 5257A plug-in.

The N switches are switched to the calculated N number, and the counters now display the input frequency being measured. (The frequency reading should be equal to N times f_2.)

Making CW and FM measurements. The initial setting of the controls for these measurements, with the exception of the level control, is identical to the setup for making a pulsed RF measurement. For this measurement, turn the level control fully clockwise, than back off one turn.

Tune the frequency control to obtain a maximum reading on the meter. Then adjust the level control to obtain a 9/10 full-scale reading. The next step is to turn the mode switch to the APC position. The meter will now read near midscale; if phase lock has not occurred, the counters will read zero. Tune the VFO to obtain phase lock, which on the meter is a midscale reading between the phase marks. Even though we have phase lock, the VFO must be further tuned to remove any phase error by tuning the VFO to obtain an exact midscale meter reading. The counters are read and recorded as f_1. Now tune the VFO to the next adjacent phase lock point, adjusted for phase error and the counter reading recorded as f_2. Using the formula for N as we did for the pulsed RF measurement, calculate N and set on the N switches. The frequency of the input signal is now displayed on the counter.

Exercises (621):

1. When tuning the frequency control of the plug-in, what indication on the counter or its plug-in shows that a zero beat has been obtained?

2. What is the maximum allowable microwave input power to the counter?

3. At what time will the display on the counters read the input frequency?

4. What type signals can be measured using the HP–5245L counter and the HP–5257A transfer oscillator?

5. When making a CW measurement, which control is adjusted if the counters read zero?

622. State the characteristics and conditions for making a frequency measurement with a direct-reading frequency meter.

Direct-Reading Frequency Meter Method. The model 532A direct-reading frequency meters offer good accuracy over an entire waveguide band. The meter consists of a variable resonant cavity coupled to a waveguide section. When tuned to resonance, a fraction of the power is absorbed; and, consequently, there is a dip of about 1 dB in the transmitting power. The frequency at which the dip on a powre-level indicator occurs may be directly from the scale on the meter.

The high-Q resonant cavity is tuned by a choke plunger. Adjustment of the plunger is by means of a precision led screw that is spring-loaded to prevent backlash.

Frequency meters of the 532A series possess good accuracy across the range of the waveguide, since the reaction at resonance is approximately constant across the rated band, and there are no spurious modes or resonances. Scale divisions are so spaced that a high order of resolution is provided.

A typical X-band frequency-measuring setup is shown in figure 2-6. A detector and power-level indicator are required to indicate the resonant point. An attenuator between the signal source and the frequency meter is necessary, since the change that occurs in line impedance at frequency meter resonance will cause a shift in the frequency of the signal source output. The amount of attenuation recommended is 10 dB or more. The indicator can be a crystal detector connected to a meter or it can be a power-measuring device.

Exercises (622):

1. When using the HP–532 series frequency meters, how is the unknown frequency identified?

2. What is the purpose of the attenuator in the measurement circuit?

3. If the direct-reading meter reads frequency directly, why is some type of indicator required to measure frequency?

2-3. Standing-Wave Ratio SWR Measurement

In the previous chapter we discussed various characteristics of transmission lines, which included VSWR. We will begin our discussion with a brief description of the front panel controls and the theory of operation of the HP–415E standing-wave ratio meter, and then discuss the measurement of VSWR.

623. Identify and state the purpose of the front panel controls of the HP–415E standing-wave ratio meter.

Controls. The major controls and connections are located on the front panel of the meter. Figure 2-7 shows the front panel controls and connectors.

pages tightly bound

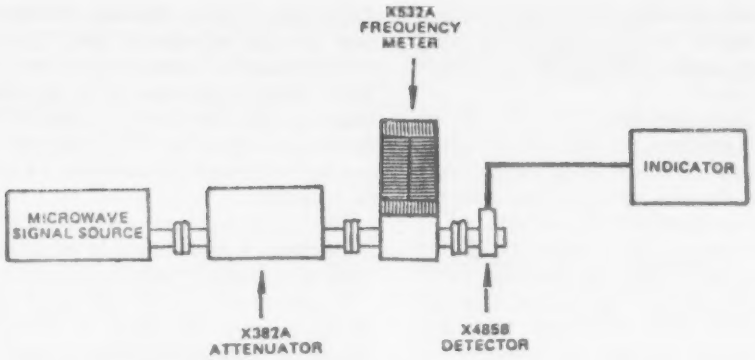


Figure 2-6. Typical X-band frequency measuring setup.

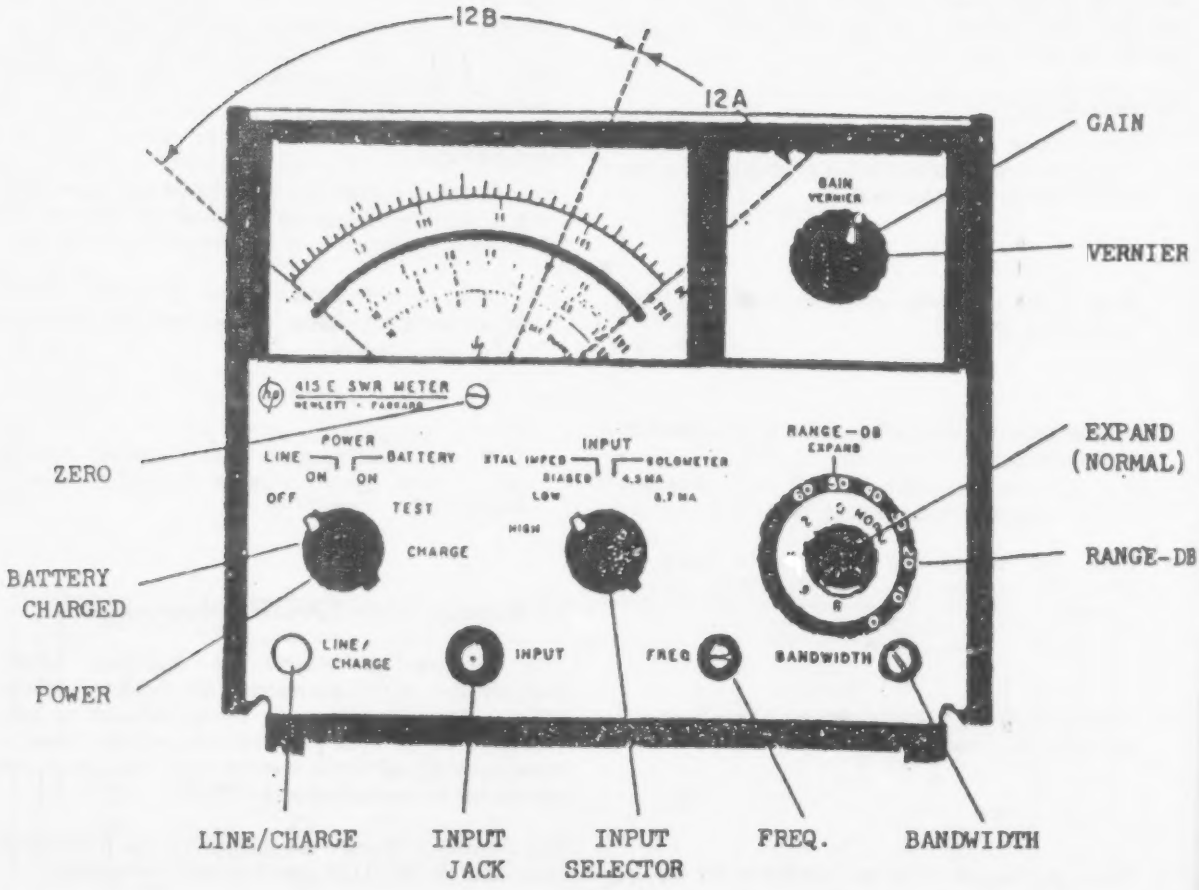


Figure 2-7. HP-415E standing-wave ratio meter, front panel.

Power. This switch selects the desired 415E power source. The BATTERY/CHARGE position allows internal battery recharge when the power cord is connected to AC line.

Line/charge. The indicator lights when power is in the LINE/ON or BATTERY/CHARGE position.

Input jack. A female BNC input connector to connect the audio measurement signal to the meter.

Input selector. An input selector switch that can be set to either crystal impedance (XTAL IMPED) or bolometer. If the switch is set to XTAL IMPED, either HIGH or LOW impedance can be selected for unbiased crystals or biased for those crystals that require bias.

Freq. A screwdriver adjustment that allows the center frequency to be varied a total of 70 Hz.

Range dB. A gain control that is adjustable in 10 dB steps.

Expand (normal). An offset switch which permits full-scale expansion of any 2 dB sector of the unexpanded meter reading. It is set to the figure corresponding to the lowest dB reading of the expanded sector desired as read on the lower dB scale. When expanded, you should read the value on the upper dB scale and then add the number of dB on the expand dial to the reading.

Bandwidth. A screwdriver adjustment that varies the bandwidth from 15 to 130 Hz.

Gain. The gain allows initial meter reference setting with a control range of at least 10 dB.

Vernier. The vernier provides fine adjustment of the gain control meter settings.

Zero. A mechanical zero adjustment that allows you to make an exact setting of the meter needle to 2 dB on the upper dB (expand) scale.

Battery charged. With the power switch set to BATTERY/TEST, a meter needle indication within the battery charge area on the meter face (indicated by 12A) shows that the internal battery is charged sufficiently for proper instrument operation.

Exercises (623):

1. In which position should the input selector switch be set for use with unbiased crystals?

2. What is the range of the bandwidth adjustment?

3. What is the total amount that a frequency adjustment can be varied?

4. The zero adjust allows the meter needle to be exactly set to on the upper dB scale.

624. Specify the operating characteristics of the HP–415E SWR meter and describe its operation.

Standing-Wave Ratio Meter. The HP–415E SWR meter is a high-gain tuned amplifier which takes an input from a bolometer, crystal, or any audio source, amplifies it, and applies it to a meter calibrated for use with square-law detectors. With bolometer or biased crystal operation, the HP–415E supplies the appropriate bias current. Figure 2-8 is a block diagram which illustrates instrument operation.

Input circuits. The input voltage is first routed through the input switch, A1S1. In the HIGH position it is applied directly to the first section of the range attenuator, A2S1. When the input switch is set to any other position but HIGH, the input signal passes through transformer T1 whose turns ratio provides a 50 to 1 impedance transformation, converting a 50- to 200-ohm source to 2500 to 10,000 ohms which is the range of the best noise figure for the input amplifier.

Range attenuator. The signal from A1S1 is fed to the first section of the range-dB switch, A2S1, and then to the input amplifier. The second section of A2S1 is located between the input amplifier and the second amplifier. The range-dB switch positions are marked in 10 dB steps.

Input amplifier. After passing through the first section of the range attenuator, A2S1, the signal goes to the input amplifier which consists of four transistors in cascade. The gain and vernier controls are associated with the final amplifier and vary its gain over a range of more than 10 to 1. The gain control is a 250-kilohm variable resistor which adjusts the amount of negative feedback from the collector of the output stage to the emitter of the input stage. The vernier control is a fine gain control which changes the gain by inserting 0 to 5000 ohms in series with the output signal.

Second amplifier. The second amplifier amplifies the signal from the second section of the range attenuator. AC feedback provides gain stability and high input impedance. The output of the amplifier is applied through the expand attenuator A2S2, to the third amplifier.

Expand circuit. The function of the expand switch A2S2 is to allow any signal level to be measured on an expanded scale with continuous coverage while maintaining the original reference level.

Frequency selective circuits. The frequency response of the third amplifier is shaped by negative feedback. The feedback path includes a Wien-bridge and amplifier. At the null frequency of the Wien-bridge, the negative feedback path is open and the gain of the amplifier is maximum. Off center-frequency the negative feedback through the Wien-bridge reduces gain. The amount of the off-resonance gain reduction depends on the setting of the bandwidth control.

Final amplifier. The output amplifier consists of four transistors. The two output transistors operate as a push-pull, class B amplifier with both collectors AC grounded. The emitters of these transistors are tied together and the AC amplifier output is taken from this point through a coupling capacitor. Large negative feedback makes the gain of the output amplifier near unity.

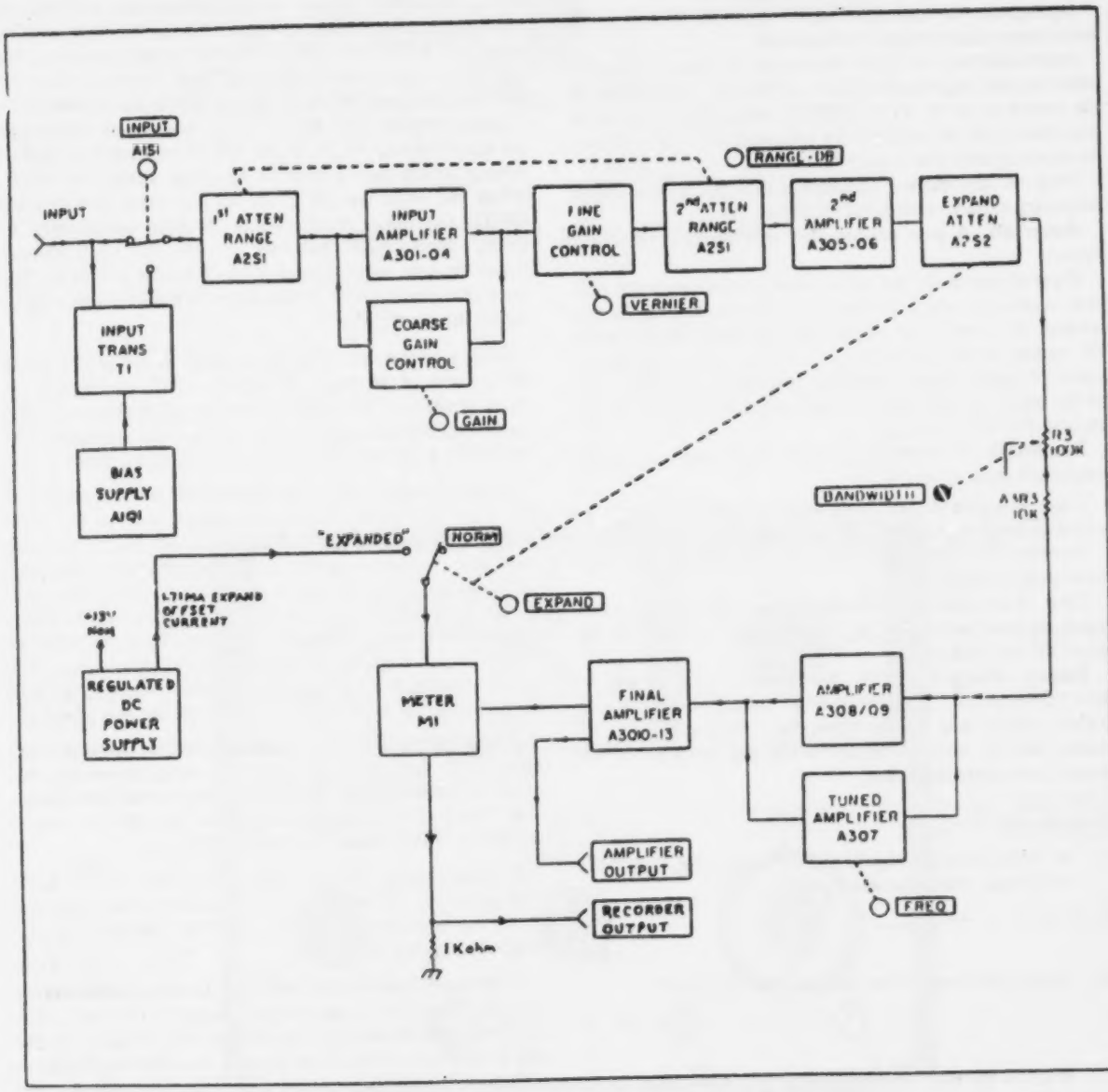


Figure 2-8. HP-415E SWR meter, block diagram.

Ground Loops. The grounding technique used in the HP–415E consists of an input connector ground, a circuit board ground, and output connector grounds. These are floating grounds that are tied together and isolated from chassis ground except for a 46.4-ohm resistor and a 0.05-microfarad capacitor connecting ground and chassis. A solid connection to chassis-or-earth ground permits troublesome ground loop currents to flow causing erroneous instrument operation. For this reason, connecting grounded instruments to the 415E output connectors can cause erroneous readings. Most recorders and oscilloscopes that might be used with the 415E outputs have differential inputs available with neither side grounded.

Input Impedance. The HP–415E is designed to have an input impedance much higher than that of any crystal detector or bolometer normally used with it. This results in lower noise figure and the highest possible input signal to the 415E. For example, with the 415E input switched to LOW, the input impedance is approximately 2000 ohms while the output or source impedance of a bolometer is approximately 200 ohms. This high input impedance effectively nearly doubles the output voltage of a source compared with an amplifier which matches the source resistance. It should be emphasized that the transformer turns ratio in the 415E is chosen for the lowest noise figure rather than to match impedances.

Input Biasing. When the HP–415E input switch is set to one of the biased positions (XTAL IMPED/BIASED, or 4.5 mA or 8.7 mA), a bias source is connected in series with the input connector. An emitter follower in the bias current path provides bolometer protection by limiting transients when a bolometer or crystal detector is connected or disconnected. Three calibrated levels of bias are available: 1 volt into 1000 ohms (XTAL, IMPED/BIASED), or 4.5 mA and 8.7 mA into 200 ohms, selected with the input switch, A1S1. These bias levels are set within ±3 percent, by adjusting the DC voltage potential of the positive power supply. A single adjustment suffices, since one percent resistors accurately determine the ratios between the three bias levels. The positive DC voltage is typically 13.2 volts DC but may be as low as 12 volts DC or as high as 14 volts DC for proper adjustment.

Power Supply. The regulated power supplies are fed by either an internal battery, BT1, or a conventional AC supply. The power supply must provide two regulated outputs: +13 volts and −1.71 millamperes offset current. In the LINE/ON position, about 3 mA trickle charge is supplied to the battery BT1. If the power switch is set to BATTERY/ON position, battery current passes through to the regulators. The BATTERY/CHARGE position allows recharging of the battery, by allowing 20 to 30 mA of current to flow to the battery depending upon its charge condition.

Exercises (624):

1. The range-dB switch positions are marked in steps of what?

2. What provides gain stability and high input impedance in the second amplifier circuit?

3. How is the frequency response of the third amplifier shaped?

4. What can cause erroneous readings when you are using the HP–415E output connectors?

5. What is the approximate input impedance of the HP–415E when the input switch is in the LOW position?

o. What are the two regulated outputs from the HP–415E power supply?

625. State the procedures for making SWR measurements, and list the sources of SWR measurement errors.

Use of the HP–415E in SWR Measurement. A typical setup of equipment used in SWR measurements is shown in figure 2-9. The signal source is usually square-wave modulated at 1000 Hz since other modulating waveforms often cause undesirable frequency modulation of the source. Harmonics from the source sometimes cause trouble and can be eliminated with a low-pass filter.

The detector should be a square-law device (output voltage proportional to the RF power input) such as a barretter or a crystal diode operated at low signal levels. The meter of the 415E is calibrated for square-law detectors. Crystal diodes are normally more sensitive than barretters but barretters are square-law over a wider dynamic range. Both types of detectors normally maintain accurate square-law response up to at least full scale deflection with the range-dB switch set to the 30 dB position and coarse gain at maximum.

A short circuit termination is useful in establishing reference positions along the transmission line and in measuring transmission line wavelengths.

Slotted line probe penetration. A general rule in slotted line measurement is to use minimum probe penetration that still picks up adequate signal to measure. The probe couples to the transmission line as a shunt admittance which increases (disturbing the transmission line more) as the probe penetrates farther. To find out whether a given probe penetration is too great or not, measure SWR, then change probe penetration and remeasure SWR. If the second

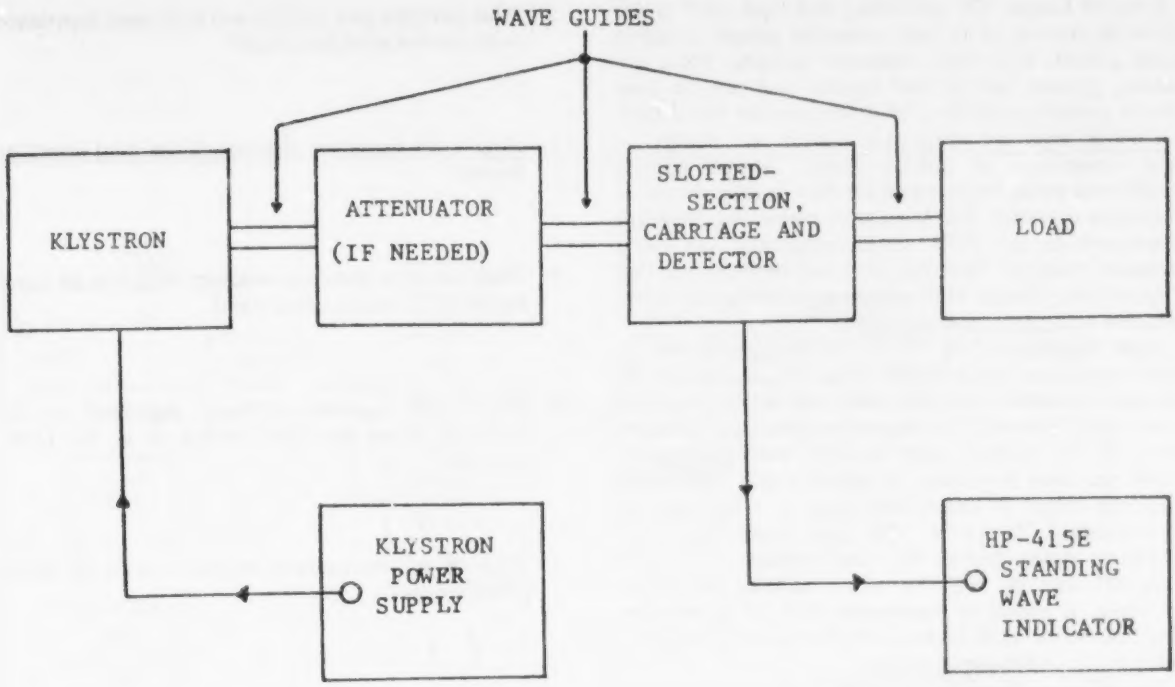


Figure 2-9. Typical setup for SWR measurement.

reading is different, the probe is penetrating too far and loading the transmission line significantly.

Use of crystal detectors. The input impedance of the HP–415E must always be higher than the output or source impedance of a bolometer or crystal detector connected to the input connector. For low output impedance devices, such as 100 to 200 ohm detectors, use the XTAL IMPED/LOW switch position on the 415E. For high output impedance devices use the XTAL IMPED/HIGH position. If improper input impedance is selected, the crystal detector may depart from square-law for which the 415E is calibrated.

Moderate SWR. Refer to figure 2-9 for a typical SWR measurement setup. The scales of the HP–415 are calibrated to read the standing-wave ratio directly.

High SWR. High standing-wave ratios (greater than 30, or sometime 10) present problems because of excessive probe penetration (to lift the minimum above the noise level) and departure of detector behavior from square-law. Both problems are lessened or eliminated by measuring only the standing-wave pattern near the voltage minimum, where probe loading effects are least disturbing.

Twice-minimum power method. The basis for this method (and the ten-times minimum power method) is the fact that for a high SWR the standing wave pattern approximates a parabola in the vicinity of a voltage minimum. The slotted line carriage must have a good scale or dial indicator. Measure the distance ($\pi\Delta\chi$) between positions on the standing-wave pattern where the voltage is 3 dB above the voltage at the minimum. Also measure the transmission line wavelength λg (standing wave pattern minima are one-half wavelength apart and the sharp minima resulting from short-circuiting the transmission line are easy to locate accurately). Compute the SWR from the following formula:

$$SWR = \lambda g/\pi\Delta\chi$$

Ten-time minimum power method. Another convenient level above minimum method to use for computing SWR is a level 10 dB above minimum. The separation ($\pi\Delta\chi$) between these positions should be put in the following formula:

$$3\,\lambda g/\pi\Delta\chi$$

The accuracy of this method is within one percent for stand-wave ratios as low as 15 to 1.

SWR measurement-sources of error. Some of the measurement sources of error are excessive frequency modulation of the source (smears out sharp, deep nulls of high SWR pattern), harmonics of signal frequency from the source, departure of the detector from square-law behavior, and excessive probe penetration. Also, reflections in the transmission line between the slotted line and the device being measured must be minimized.

Exercises (625):

1. When making SWR measurements, what is the Hertz that the signal source is usually modulated?

2. The detector used in SWR measurements should be what type of device?

3. The input impedance of the HP–415E must always be higher/lower than the output or source impedance connected to the input connector.

4. When making moderate SWR measurements, how is the standing-wave ratio read on the meter?

5. What is the accuracy of the "ten-times minimum power method" of measuring SWR?

6. What are three SWR measurement-sources of error?

2-4. 8620C Sweep Oscillator

Single frequency measurements performed at many points are not satisfactory when making measurements on wide frequency band devices due to the time involved and, even then, not all frequencies in question are covered. For this reason swept frequency measurements were developed. For these measurements we need a variable signal source. To understand swept measurements and how to make them, you must have a thorough knowledge of a signal source that has swept capabilities. The one we will cover here is the HP 8620C state of the art sweeper.

626. Identify the front panel controls of the 8620C sweep oscillator, and state the purpose.

Controls. The major controls and connections are shown in figures 2-10 and 2-11.

Front panel controls. A description of each control follows:

Start marker control R2 and full sweep pushbutton switch S4. Pressing the pushbutton switch selects FULL SWEEP mode and FULL SWEEP lamp DS1 lights. Sweep covers full band of frequencies of scale from low to high frequency. Green START MARKER lettering over control is color coded to green start pointer on scale. In FULL SWEEP mode, START MARKER control adjusts *only* Start Marker position and *not* start frequency. Three markers are available on sweep: Start Marker at position of green pointer, CW Marker at position of white pointer, and Stop Marker at position of red pointer.

Band switch S2/S3. Depressing the lever advances the drum containing the frequency scales. It also changes the position-sensing switches to activate oscillator module in RF section.

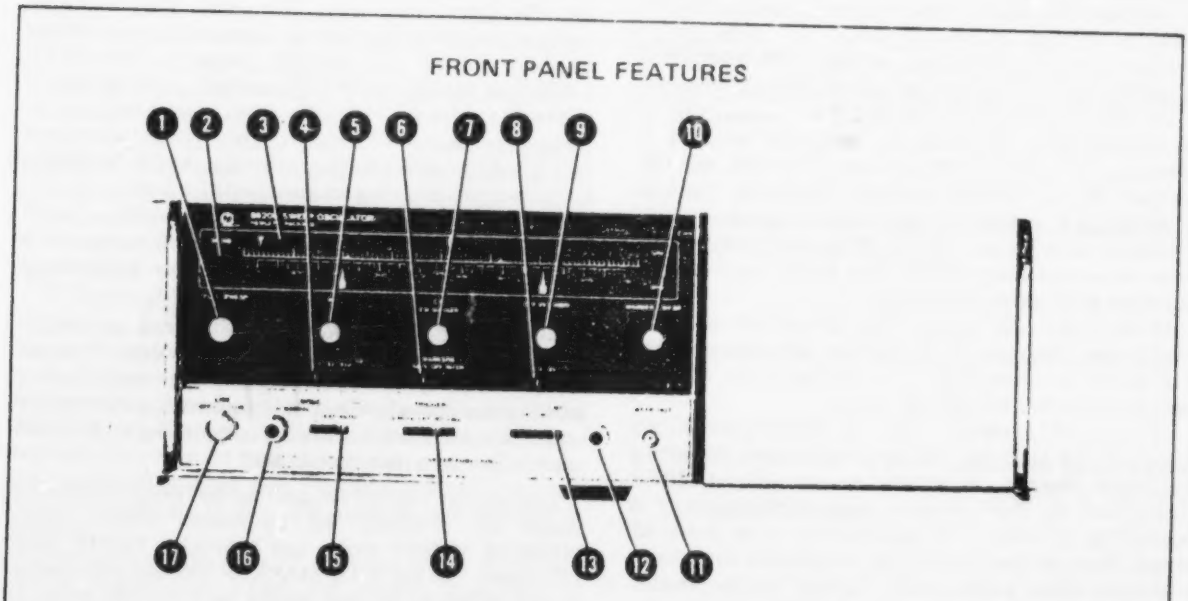


Figure 2–10. Front panel features, 8620C Sweep Oscillator.

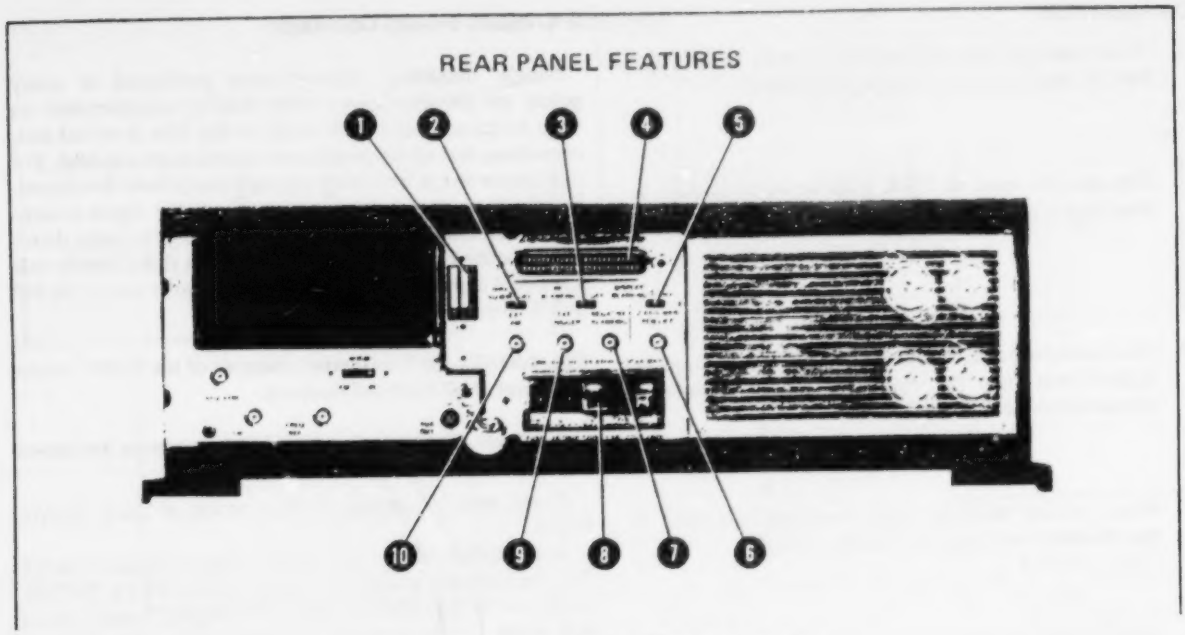


Figure 2-11. Rear panel features, 8620C Sweep Oscillator.

Frequency scale window. The band selected is displayed at the window. The top scale has pointers for START MARKER (green), STOP MARKER (red), and CW MARKER (white) controls. The bottom left scale is ΔF and the bottom right scale is CW VERNIER. A calibration scale is included in one band position for ease of calibration, but is not essential to the calibration procedure. When an additional band is added to the RF drawer, a new scale may be installed. The drum position may be identified by tick marks on left side of drum. Position "I" of the BAND drum activates the Heterodyne Module ("Position 1" in 8621A/B) and the oscillator module installed in "Position 2" of 8621A/B or band 1 of the 86290A. Position "II" of the BAND drum activates the oscillator installed in "Position 2" of 8621A/B or band 2 of the 86290A. Position "III" activates the oscillator installed in "Position 3" of 8621A/B or band 3 of the 86290A. Position "IIII" activates circuits for use with the HP Model 86290A multi-octave sequential sweep band 4. Any BAND drum position will select an 86200 series plug-in.

ΔF multiplier slide switch A9S4. Selects the multiplier for ΔF scale. When set to X1 position, ΔF scale setting is read directly and when set to X.1 or X10 positions, ΔF scale setting is multiplied by either 0.1 or 10.

ΔF control R3 pushbutton switch S5. Pressing pushbutton lights both ΔF DS2 and CW DS3 pushbuttons, indicating that center frequency is selected by the CW MARKER control and the full deviation about CW frequency is selected by ΔF control. ΔF scale is short scale above ΔF control. Start and Stop Markers are available on ΔF sweep.

Markers slide switch A9S5. Selects marker modes: AMPL, OFF, and INTEN. In AMPL position, the frequency marker is modulated on the RF sweep signal. In OFF position, no marker is present. In INTEN position a frequency marker is obtained by intensity modulating the Z-axis of the oscilloscope or other display instrument on which the sweep trace is shown. The intensity modulation signal is available at the rear-panel Z-AXIS/MKR/PEN LIFT output J8.

CW marker control R4 and CW pushbutton switch S6. Pressing the pushbutton switch selects the CW mode and the CW lamp DS3 lights. The white CW MARKER lettering over the control is color coded to the white pointer on the scale and indicates CW frequency. With FULL SWEEP or MARKER SWEEP selected, a CW Marker is available and the position of the white pointer indicates the frequency setting of CW Marker. The CW light also comes on when ΔF mode is selected, indicating the CW MARKER control selects the center frequency of ΔF Sweep.

CW vernier multiplier slide switch A9S6. Selects multiplier for CW vernier scale. In X1 position the scale is read directly and in X.1 position the scale indication is multiplied by 0.1.

CW vernier control R5 and pushbutton switch S7. Pressing the pushbutton switch connects vernier function for CW or ΔF modes. (DS4 lights.) The vernier control provides for fine adjustment of frequencies about the CW scale setting. The scale multiplier is controlled by the slides witch below the pushbutton control.

Stop marker control R6 and marker sweep pushbutton switch S8. Pressing the pushbutton switch selects MARKER SWEEP mode, and MARKER SWEEP lamp DS5 lights. The red STOP MARKER lettering over control is color coded to red stop pointer on scale. The sweep is between green START MARKER pointer and red STOP

MARKER pointer. The CW Marker is available on the sweep.

Sweep out BNC connector J1. Output is linear ramp voltage from zero to 10 volts synchronous with RF sweep signal. This output is available for all operating modes.

Time-seconds vernier control R8. Allows sweep time to be adjusted through range selected by the TIME-SECONDS slide switch.

Time-seconds slide switch A9S3. Sets range of sweep time. The sweep time may be selected from > 100 seconds per sweep (slide switch to left position and vernier control counterclockwise) to < 0.01 seconds per sweep (slide switch to right position and vernier control clockwise).

Trigger slide switch A9S2. Selects source of sweep-trigger pulse. This switch has a spring return in the SINGLE sweep mode position. Each time the switch is pressed into SINGLE position, a single sweep is initiated; when released, the switch returns to EXT. In EXT position, an external trigger pulse may be applied through the rear-panel EXT TRIGGER connector. In the INT position, a sweep trigger pulse is derived from the internal sweep oscillator and the system is free running. In LINE position, the sweep is triggered by the power line sine wave peaks.

Mode slide switch A9S1. Selects source of sweep signal. In MANUAL position, the control at left of the MODE switch controls the sweep manually. In EXT position, an external sweep signal may be applied through the rear-panel PROGRAMMING connector. In AUTO position, the sweep signal is obtained from the internal sweep oscillator, producing a continuous sweep signal.

Manual mode control R7. Allows manual sweep of frequency range selected by FULL SWEEP, MARKER SWEEP, or ΔF controls. It selects the start frequency in full counterclockwise position; selects stop frequency in full clockwise position. No markers are available.

Line, off-on switch S1. Pressing the LINE switch applies power to the mainframe and plug-in, and illuminates DS6. Applying power to the instrument always selects FULL SWEEP mode. The line on the side of the pushbutton indicates ON and OFF position.

Rear panel features. Features of the near panel follow.

Serial number and option label.

1 kHz SQ WV/OFF slide switch S9. Selects the type of amplitude modulation of signal. In OFF position, an external modulation signal may be applied through the EXT AM connector located below the switch. In the 1 kHz SQ WV position, a 1 kHz internal oscillator modulates the RF output signal.

RF blanking/off slide switch S10. This switch selects type of blanking. In RF BLANKING position, the RF signal is turned off during the retrace portion of the sweep. This mode of blanking should not be selected when the sweeper is used with a phase lock system. For example, the Model 8410B/8411A Network Analyzer requires the system to regain phase lock at the beginning of each sweep rather than stay in continuous phase lock. For phase lock operation, use the OFF position. In the OFF position, no blanking is selected.

Programming connector J2. Provides means to connect remote programming signals for standard instrument or when Options 001 or 011 are used. This input is also for the programming remote manual commands and attenuation commands. Various outputs are available such as marker, blanking, and pen lift.

Display blanking/off slide switch S11. Selects blanking for Z-Axis of display equipment during retrace. In DISPLAY BLANKING position, the blanking is applied to the Z-AXIS/MKR/PEN LIFT BNC connector located below the switch. The display instrument is blanked during the retrace but the RF signal from the sweep continues to operate during retrace. In the OFF position, there is no blanking output.

Z-Axis/MKR/PEN lift connector J8. BNC connector provides Z-axis modulation to display unit or pen lift signal to X-Y recorder. When the slide switch above this BNC connector is in the DISPLAY BLANKING position, blanking is applied to the connector. The blanking signal is a rectangular +5 volt pulse into 2500 ohms. The intensity modulation frequency marker is selected when the front-panel MARKERS slide switch is in the INTEN position. The marker signal is a rectangular −5-volt pulse into 10K ohms.

Negative blanking connector J5. BNC connector provides negative polarity blanking during retrace. The blanking signal is a rectangular −5-volt pulse into 2400 ohms.

Power line module FL1. Line voltage selector card FL1TB1 allows selection of 100, 120, 220, or 240-VAC operation.

EXT trigger connector J4. (BNC connector to input external trigger pulse). This input is selected when the front-panel TRIGGER slide switch is in the EXT position. The trigger signal must be greater than +2 Vdc, wider than 0.5 μsec and not greater than 1 MHz in frequency.

EXT AM connector J3. (BNC connector to input external amplitude modulation signal). This input is selected when the rear-panel 1 kHz SQ WV/OFF slide switch is in the OFF position.

Exercises (626):

1. What does the Start Marker control of the 8620C adjust?

2. Which markers are available during the manual mode of operation of the 8620C?

3. When shouldn't RF blanking be used on the 8620C?

4. Which control on the 8620C allows the sweep time to be adjusted through the range selected at the time-seconds slide switch?

627. Identify the different types of programming used in the 8620C, and state the purpose.

Remote Programming. The remote programming control signals are applied through the rear-panel PROGRAMMING connector.

Computer or Calculator Programming. With the addition of Option 001 (A6 BCD Programming printed circuit board), the 8620C may be programmed remotely from a computer or calculator. A simulated sweep model is provided by sequentially selecting up to 10,000 point frequencies for each band. Band switching, RF attenuation (with 8621B Option 001) and remote/manual operation may also be programmed from the computer.

The Option 001 BCD programming provides the same capabilities as the HP–IB Option with the exception that no digital marker is available in the programmed sweep modes.

Hewlett-Packard Interface Bus (HP–IB). With the addition of option 011, a capability is provided to control the sweeper directly via the HP interface bus. With Option 011 installed, any sweep function (ΔF, FULL SWEEP, etc.) can be selected and the 8620C will sweep according to the front-panel frequency settings. This option provides a flexible, digital frequency programming with a resolution of 10,000 points per band or 10,000 points across the frequency range set by the front-panel controls. With this operation, a programmable digital marker is available.

Manual Remote Programming. A manual remote control system may be used where repetitive operations are performed. The standard 8620C (without Options) contains remote control circuits to select operating mode and frequency range. This mode can be calculator or computer controlled.

NOTE: Examples in the following section are written using the HP Model 9830A Calculator with HP Model 59405A Option 030 HP–IB Calculator Interface.

HP–IB Remote Programming Instructions. The 8620C Option 011 sweeper is a remote programmable instrument designed for use in systems that interface with the HP–IB. The front-panel sweep modes that are programmable include FULL SWEEP, ΔF SWEEP, CW, and MARKER SWEEP. Control voltages (from a remote-control source) tune the frequency in FULL SWEEP, ΔF SWEEP, and MARKER SWEEP modes. Also, a remote control voltage tunes a remote marker in Local operation. The selection of bands 1 through 4 is programmable and one code is available to place the 8620C in local band control.

Interface Modes of Operation. The HP–IB uses two modes to communicate between instruments: Command Mode and Data Mode. During Command Mode, the system controller addresses the instrument to be programmed. The ASCII "&" character is the example address for the 8620C used in this manual. During Data Mode, codes are sent that are instructions for the instrument addressed to listen. In Data Mode, there are no specific code assignments but devices communicating must agree on the meaning of the codes used.

The structure for a typical system controller statement would be:

CMD "?U&", "DATA"

Where "?" is the universal ASCII unlisten command to re-initialize the bus, "U" is the calculator talk address, and "&" is the sweeper listen address. The data string follows the address mode. Quotation marks are needed to obtain the keyboard alpha characters and the comma separates the address string from the data or instruction string. The "?U" preceding the 8620C listen address (&) clears the previously addressed instruments and re-addresses the calculator as a talker. (A complete summary of the programming codes is in Table 2-1.)

Mode Selection. The HP Model 8620C Option 011 allows several modes of digital and analog frequency control via the HP–IB. These modes are summarized in Table 2-1.

In Mode M1, the output frequency is totally independent of front panel control settings and offers 10,000 points of frequency resolution per band for fine frequency selection.

For even more resolution, Modes M2 and M4 are available. In these modes, the digital frequency resolution is determined by the front-panel frequency control settings on the 8620C. For example, with Mode M2 selected, the front-panel CW control set at 7.5 GHz, and the ΔF control set at 1 GHz, the source would have a digital frequency resolution of 10,000 points between 7.0 GHz and 8.0 GHz or a minimum increment of 100 kHz. The START MARKER and STOP MARKER controls might then be set at 8.0 and 9.0 GHz respectively allowing 10,000 points resolution between those settings in mode M4. In combination, this would provide a resolution or minimum increment capability of 100 kHz from 7.0–9.0 GHz in modes M2 and M4.

Often, it is desirable to be able to view a dynamic swept display, especially during set-up and fine-tuning of a device prior to final test, or as a quick preview to ensure no gross discontinuities exist. Modes M5, M6 and M8 allow this flexibility. Mode M5 produces an analog sweep of the full band selected. Sweep speed, sweep mode, and trigger are all determined by 8620C front-panel controls. Simiiarly, modes M6 and M8 produce analog ΔF and MARKER SWEEP as determined by appropriate front panel control settings. In these three modes, mainframe markers or a digitally programmed marker are available.

The capability to place the sweeper in mainframe-controlled CW mode is provided in modes M3 and M7. This allows the operator to manually set CW frequencies or, with a counter, to accurately set the center frequency for ΔF modes.

If no mode is programmed, the sweeper retains its most recent mode. At the initial turn-on of the sweeper, it is in mode M5.

Band Programming. Any of the four bands of the 8620C Option 011 may be selected externally via the HP–IB.

Band 1 through 4 are designated simply by the ASCII characters "B1" through "B4." In addition, band selection control may be returned to the 8620C front-panel

TABLE 2–1
PROGRAM MODES

	Description	ASCII Code
Digital Modes	0.000 Volts → Low End of Band Selected = F_L 10.000 Volts → High End of Band Selected = F_U	M1
	0.000 Volts → Setting of Front Panel CW Control Minus $\frac{\Delta F \text{ Setting}}{2} = F_L$ 10.000 Volts → Setting of Front Panel CW Control Plus $\frac{\Delta F \text{ Setting}}{2} = F_U$	M2
	0.000 Volts → Setting of Front Panel Start Marker = F_L 10.000 Volts → Setting of Front Panel Stop Marker = F_U	M4
Analog Sweep Modes	Analog Sweep of Full Band Selected	M5
	Analog ΔF Sweep Controlled by Front Panel ΔF and CW Controls	M6
	Analog Marker Sweep Controlled by Front Panel Start- and Stop-Marker Controls	M8
Analog CW Mode	Output = Front Panel CW Control Setting	M3 or M7

lever by programming "Bϕ." At turn-on, the sweeper is in Bϕ. As with mode programming, the sweeper retains its most recent band instruction if not instructed otherwise. See Table 2-2 for a list of all band programming.

Band programming capability is most useful with the multi-band plug-ins such as the 86290A 2-18 GHz plug-in and the 8621B RF drawer with HP 86300 series RF modules. Since the 86200 series of single-band plug-ins will operate equally with any band selected, this instruction is not necessary.

Frequency (Voltage) Programming. Since the YIG-tuned oscillators in the 8620 plug-ins are essentially VCOs, the programming instructions are in volts or millivolts. This allows the flexibility to use a large number of frequency plug-ins covering a wide variety of bandwidths and absolute frequencies.

For this reason, it is necessary to use the calculator to convert desired frequency to the required voltage information. This involves a simple conversion equation:

$$V_X = \frac{F_X - F_L}{F_U - F_L} \times 10$$

Where F_X = lower frequency limit of the Mode selected (see Table 2-1)
F_U = upper frequency limit of the Mode selected (see Table 2-1)

TABLE 2–2
BAND PROGRAMMING (ALL MODES)

Description	ASCII Code
Local Band (As Selected by Front-Panel Lever)	Bϕ
Band 1	B1
Band 2	B2
Band 3	B3
Band 4	B4

TABLE 2–3

FREQUENCY (VOLTAGE PROGRAMMING (MODES M1, M2, M4)

0.000 Volts correspond to low end of band and mode selected 10.000 Volts correspond to high end of band and mode selected.		
Examples		
Frequency (% of Band/Mode)	**Voltage Required (Volts)**	**ASCII Codes**
0%	0	VϕE or Vϕϕϕϕϕ
0.1%	0.01	V.010E or V10E
55%	5.5	V5.500E or V5500E
100%	10.000	V:.000E or V:000E

The 8620C Option 011 requires the following format to output the proper frequency: "Va.bcdE." The letter "E" indicates the end of the voltage string. The decimal point is optional and is disregarded by the sweeper. It processes up to 4 digits of information and assumes the information is in millivolts with leading zeros suppressed. If more than 4 digits come down the HP–IB, the 8620C processes only the four digits immediately preceding the "E" (Table 2-3).

EXAMPLE: With this information, we are prepared to execute an example using literals for the programming information. In this and following examples, we will use the 86290A 2–18 GHz plug-in with the 8620C. It has four bands covering 2–6.2 GHz, 6–12.4 GHz, 12–18 GHz, and 2–18 GHz respectively. Bands 1 through 3 allow greater resolution than band 4; so, in general, we will be more likely to use these narrower bands than the full 2–18 GHz band.

Let's assume the desired output frequency is 15 GHz. One approach is to use Mode M1 and band B3. The required voltage is then:

$$\frac{15-12}{18-12} \times 10 = 5.000.$$

The calculator statement required to output 15 GHz is:

```
10 CMD "?U&", "M1B3V5,000E"
```

Note that the order of execution is unimportant, (i.e., GMD "?U&". "B3V5000EM1" would produce the same results). Note also that the 3 zeros must be present after the "5" whether or not the decimal point is present.

As mentioned above, if more than 4 voltage digits travel down the HP–IB, only the last 4 are processed. What if the frequency desired is the same as F_U? This would require 10.000 volts. Only the last four zeros would be processed resulting in F_L instead of F_U! To obtain 10 volts or more, there is a special ASCII character which signifies 10. The character is the colon (:). For 18-GHz output, the above string would be modified to:

```
10 CMD "U&", "M1B3V:000E"
```

Markers. In modes M5, M6, and M8, a digitally programmed marker is available in addition to the standard mainframe markers. The programmable marker is selected by outputting the ASCII character "R" (which also disables the mainframe marker). The frequency of the marker is dictated by a voltage string programmed in the same manner as the digital frequency described above with F_L and F_U being the end points of the band selected. For example, to obtain a marker at 14 GHz in modes M5, M6, or M8, the following string is required:

```
10 CMD "?U&", "B3V3333ER"
```

This will result in either an AMPLitude or INTENsity marker dependent on the setting of the 8620C front-panel switch. In this mode, the mainframe-controlled markers are disabled.

To enable the mainframe markers and disable the programmable marker, output the ASCII character "L." This places the markers into totally local control. See Table 2-4 for a summary of all programming codes.

Format Statements. In order to program the frequency with variables, a format statement is required to ensure the proper characters and sequence are used on the HP–IB. For the Band and Mode information, suppression of leading zeros is required. With the frequency information in volts, 3 digits are required after the decimal point and again it is desirable to suppress leading zeros.

EXAMPLE: In this example, the variable B is defined as the band number, X is defined as the voltage required, and mode M1 is used to output a CW frequency. The following program steps would output the proper frequency:

```
9825A


O:

cmd7, "?U&" ;fmt1"M
1B",f.0,"V",f.3,
"E"
1:
wrt 706.1,B,x


9830A


10 CMD "?U&"
20 OUTPUT (13,30)B,X
30 FORMAT "M1B",F1000.0, "V",F1000.3,"E"
```

There are two ways to handle $\geq$ 10 volts when programming in variables. If F_U is desired to the accuracy of the sweeper, a conditional statement resetting X to 9.999 whenever it is greater than or equal to 9.9995 will produce virtually 10 volts and a frequency within 0.005 percent of that produced with 10.000 volts. For frequency correction (see example below) or where frequencies $\geq F_U$ are required, a conditional output statement may be used. If X is $\geq$ 9.9995, then the program would branch to the following output steps:

TABLE 2–4
SUMMARY OF PROGRAMMING CODES

CODES		FUNCTION	DESCRIPTION
MODE SELECTED	M1	FULL SWEEP	Remote control voltage of 0V corresponds to the low frequency end of the band and control voltage of 10V represents the high frequency end of the band.
	M2	ΔF	Remote control voltage of 0V represents CW − (ΔF WIDTH/2) and control voltage of 10V represents CW + (ΔF WIDTH/2).
	M3/M7	CW	Frequency corresponds to position of CW pointer.
	M4	MARKER SWEEP	Remote control voltage of 0V represents the START pointer frequency and control voltage of 10V represents the STOP pointer frequency.
	M5	FULL SWEEP	FULL SWEEP control operates same as in local operation.
	M6	ΔF	ΔF control operates same as in local operation.
	M8	MARKER SWEEP	MARKER SWEEP control operates same as in local operation.
BAND SELECTED	B1	Band 1 select	
	B2	Band 2 select	
	B3	Band 3 select	
	B4	Band 4 select	
	B0	Local Control	Front-panel BAND lever selects the band.
MARKER MODE	L	LOCAL MARKERS only	Markers selected in Sweep Modes M5, M6, and M8.
	R	REMOTE MARKERS only	

9825A.

```
8:
cmd7,"?U&";fmt2"M
1B",f.0,"V:",f.3
,"E"
9:
wrt706.2,B,x-10
```

9830A.

```
70 CMD"?U&"
80 OUTPUT (13,90)B,X-10
90 FORMAT"M1B",F1000.0,"V:",F1000.3,"E"
```

HP 8620C HP–IB configuration code. The programming configuration code for the 8620C, as documented in IEEE Standard 488–1975 for the HP–IB, and selected by the calculator is:

SH0 AH1 T0 L2 SR0 RL2 PP0 DC0 DT0 C0 E1

Remote/Local Operation. The term remote/local refers to which device is controlling the 8620C sweeper. In local, the front panel of the sweeper has control; in remote, the calculator or computer is in control. Three conditions of the Local/Remote/Return-to-Local selection are explained.

Power-on conditions. When the 8620C is first turned on, it is in Local Control.

Remote control. To set the 8620C to Remote, the HP–IB must be in remote (REN true) and the 8620C must receive its listen address. REN must be held true continuously to remain in remote control. When set to Remote control, the programming and conditions will be as follows:

Mode:	Determined by mode set on front panel; Codes M5, M6, M7, and M8.
Band:	Set by front-panel level switch; Code B0.
Control Voltage:	V is undefined.
Marker:	Set to local; Code L.

Return-To-Local. The 8620C may be returned to local control by setting REN false, turning the 8620C or controller power OFF, or removing the HP–IB cable from either the 8620C or controller.

Addressing. All instruments using the HP–IB share a common set of data and control lines. Since the controller must communicate with individual instruments on the bus, each instrument is given a unique address. The address is a 7-bit ASCII character (American Standard Code for Information Interchange) that the instrument recognizes and responds to.

Before addressing an instrument, the controller first pulls the ATN (attention) control line low (true) and then, during Command Mode, the address code is transmitted. When the instrument acknowledges receipt of the address (through the handshake lines), the controller releases the ATN line and clears the address code. The 8620C can be addressed (or unaddressed) in both local and remote control modes.

Listen address codes. In an HP–IB system, the 8620C Option 011 functions as a listener. A *listener* is a device capable only of receiving data or commands from other instruments. The 8620C is enabled as a listener when the controller transmits the correct listen-address code. The 8620C HP–IB interface ignores all commands or addresses relating to talkers or controllers.

The 7-bit codes reserved for listen addresses and the corresponding ASCII character are listed in Table 2-5. (A total of 31 addresses are available.) Bits one through five of the data (DIO) lines are set either high or low to select the address. The address code is set with five address switches. A12SW1–1 - A12SW1–5 on the A12 HP–IB interface assembly.

TABLE 2–5
LISTEN ADDRESS CODES

Listen Addresses					
Bits					ASCII Character
b_5	b_4	b_3	b_2	b_1	
0	0	0	0	0	SP
0	0	0	0	1	!
0	0	0	1	0	"
0	0	0	1	1	
0	0	1	0	0	$
0	0	1	0	1	%
0	0	1	1	0	&
0	0	1	1	1	'
0	1	0	0	0	(
0	1	0	0	1	)
0	1	0	1	0	*
0	1	0	1	1	+
0	1	1	0	0	
0	1	1	0	1	—
0	1	1	1	0	.
0	1	1	1	1	/
1	0	0	0	0	0
1	0	0	0	1	1
1	0	0	1	0	2
1	0	0	1	1	3
1	0	1	0	0	4
1	0	1	0	1	5
1	0	1	1	0	6
1	0	1	1	1	7
1	1	0	0	0	8
1	1	0	0	1	9
1	1	0	1	0	:
1	1	0	1	1	;
1	1	1	0	0	<
1	1	1	0	1	=
1	1	1	1	0	>

The nominal 8620C listen address is ASCII character "&" or octal 046. The address may be changed by the system designer since the 8620C does not require any particular address. When changing addresses, be sure the new address does not conflict with those of other instruments using the HP–IB.

Unaddressing. Once the 8620C is addressed, it remains addressed until it is unaddressed or cleared by the system controller. There are several ways to unaddress the 8620C:

a. Sending unlisten command (077 octal ASCII ?). This command must be given in the Command Mode (ATN true).

b. Pulling interface clear (IFC) line true. This asynchronously clears all instruments on the HP–IB.

c. Turning 8620C mainframe OFF.

Response Timing Consideration. The time required by the 8620C to accept each character is approximately 5 μsec. Any change of frequency in the plug-in will need 10 msec or less for stepping across the entire band and proportionally less time for smaller changes in frequency. (This time delay is required by the 8620C after the command is received and is due to inherent delays in the oscillator.)

Bus Operating Considerations. When a device capable of activating IFC is powered ON during system operation, it may cause the active controller on the bus to relinquish control, resulting in errors. The controller must transmit IFC to regain active control.

Prior to addressing new listeners it is recommended that all previous listeners be unaddressed using the Unlisten Command "?".

Exercises (627):

1. What is the programming that is applied through the rear panel programming connector of the 8620C known as?

2. The Option 001 BCD programming provides the same capabilities as the HP–IB Option with what exception?

3. The HP–IB, with the addition of Option 011, provides what capability to the 8620C?

4. How many modes does the HP–IB use?

5. What type of oscillators are used in the 8620C?

6. When is band programming most useful?

7. What section can be used to unaddress the 8620C once it is addressed?

8. Prior to addressing new listeners, what is recommended for all previous listeners?

CHAPTER 3

Microwave Power Measurements

CALIBRATION and repair of equipment peculiar to power measurement are your responsibility as a PME specialist. The applicable technicals in the 33K series give the sequence to be followed. This will, therefore, present knowledge you will need to perform these duties more proficiently.

During this discussion, we will examine some of the more common bolometer mounts, an average power measuring device, a peak-power measuring device, a RF power subsystem, and certain principles applicable to calibration in the microwave power measurement area.

3-1. RF Power Amplifier Subsystem Model SSPA 0240–22/6140

The M/A-Com MPD Model SSPA 0240-22/6140 RF amplifier subsystem is a solid-state system designed to amplify low-level RF input signals up to a sufficient output level, adjustable to 200 watts over the frequency range of 2 to 400 megahertz in twelve bands. The amplifier subsystem is comprised of two self-contained RF amplifier units (A1, A2) and a filter switching unit (A3).

628. Specify operating characteristics of the SSPA 0240–22/6140 RF Amplifier Subsystem.

Operating Characteristics. Each amplifier is equipped with an integral high efficiency power supply to provide the required operating potentials. The 2 to 100 megahertz amplifier (A2) actually consists of two separate amplifiers (2–30 megahertz and 30–100 megahertz) housed in the same enclosure. The 100 to 400 megahertz amplifier (A3) is housed in a separate enclosure. The filter switching unit (A1) contains twelve low-pass filters for each of the subsystem's operating bands. In addition, it contains protection circuitry to prevent damage to the integral coaxial switches due to hot switching while RF output is line.

The subsystem is equipped with other protection circuitry to prevent damage due to excessive load VSWR, excessive forward power, and RF overshoot conditions. This same protection circuitry is used to provide leveled RF output of the subsystem over each frequency band despite any slight input signal level variations. Finally, built-in test (BIT) circuitry permits rapid fault isolation to the defective module level.

Exercises (628):

1. The 2 to 100 megahertz amplifier (A2) consists of how many amplifiers?

2. Can the filters of the SSPA 0240–22/6140 be switched with RF power on? Explain your answer.

629. State facts about the protection circuitry of the SSPA 0240–22/6140.

Protective circuitry. The following paragraphs detail the subsystem's various protection and control mechanisms. Note that each amplifier is equipped with four major components (Input Stage, Directional Detector, Main Control Board and Auxiliary Control Board) of the protection circuitry. The filter switching unit houses the remaining two major protection circuit components; the Control Board (A1) A1, and the Dual Directional Detector (A1) A3. The function of each major component is indicated beginning with the input stage and ending with subsystem output levelling.

Input stage. The input module contains two portions of the protection circuitry. A detector which provides an output signal proportional to the input signal level and a pair of mixers, operating as current controlled attenuators. The mixers serve to adjust the overall gain of the amplifier.

Directional detector. At the output of each amplifier, this module couples the reflected portion of the output signal, and provides a DC signal proportional to the reflected RF level.

Main control board. The "heart" of the protection circuitry, this board processes various system operating information and generates control current to the current controlled attenuator portion of the input stage to effect turn down of RF during fault conditions, and to provide levelling of the output signal during normal operation.

Auxiliary control board. This board senses RF input and generates an alarm signal to the main control board to turn down RF and prevent RF overshoot (during equipment turn on). In addition, this board monitors the reflected output level of the amplifier (via the directional detector) and

similarly effects RF turn-down in the event of excessive reflected power.

Control board. In the filter switching unit, this board performs two basic protection functions:

(1) Hot switching protection is accomplished by generating an alarm signal to the amplifier's main control board in the event that band selection is attempted while RF output is present.

(2) Output level control is accomplished be generating a control signal to the main control board in response to the output level selected.

Dual directional detector. In the filter switching unit, this module provides separate forward and reflected detected output signals proportional to the respective RF levels.

RF overshoot protection. To prevent damage to the system from an RF overshoot condition during turn on while an RF input is applied, the detector portion of the input stage provides a signal to the auxiliary control board.

This signal causes an output signal to be generated to the main control board for an interval of time sufficient to enable the various other protection circuits to stabilize. The main control board, in turn, generates control current to the current controlled attenuator portion of the input stage to effect RF turn-down during the interval. After stabilization, the control signal from the auxiliary control board is gradually reduced, thus permitting the main control board to gradually reduce control current to the current controlled attenuator, and thus providing a gradual turn on of RF power.

Amplifier reflected power protection. In the event of a fault which would cause excessive reflected power at the amplifier output, the directional detector will generate a signal to the auxiliary control board. The auxiliary control board, in turn, will generate a signal to the main control board to reduce the RF input level via the current controlled attenuator portion of the input stage.

Hot switching protection. Permanent damage could occur to the subsystem if the operating frequency band is inadvertently altered while RF output is present. While this is definitely not the normal operating procedure, provisions have been included in the subsystem to preclude this type of fault. A portion of the detected input signal from the amplifier's input stage is applied to the control board of the filter switching unit. In the event that the band select input is changed while the RF input is present (from any of the amplifiers), an alarm signal is generated by the filter switching unit's control board. This alarm signal is applied directly to the amplifier's main control board in order to cut off RF drive via the current controlled attenuator portion of the input stage.

Subsystem reflected power protection. In the event of a fault in the external RF load circuit which would cause excessive reflected power at the filter switching unit output, the dual directional detector will generate a signal to the main control board of the amplifier. The main control board will then cause RF to be reduced to a safe level via the current controlled attenuator portion of the input stage.

Subsystem output levelling. In order to provide a constant output level, regardless of slight variations in the RF input level, the forward and detected output of the filter switching unit's dual directional detector is utilized. This signal is applied to the main control board of the amplifier. The main control in turn, varies the insertion loss of the current controlled attenuator so as to maintain a constant output power level.

RF output level select control. In order to provide adjustment of the subsystem output, a voltage generated by the main control board is passed through a variable resistor (R1A–R3B) in the filter switching unit. The adjusted output voltage is then passed back to the main control board in order to provide adjustment of amplifier gain via the current controlled attenuator portion of the input stage.

Exercises (629):

1. How many portions of the protection circuitry are contained in the input stage?

2. Which board in the SSPA 0240–22/6140 is the "heart" of the protection circuitry?

3. Is the internal circuitry of the SSPA 0240–22/6140 protected against a fault in the external RF load? Explain your answer.

3-2. Bolometer Mounts

A bolometer is a specially constructed element of temperature-sensitive material. The active material can be a short, ultra-thin wire (barreter) or a semiconductor material bead supported between two pigtail leads (thermistor). Although there are other types of bolometers used to measure low power at high frequencies, barreters and thermistors are the most common.

When RF power is applied to a bolometer element, the power absorbed by the element heats it and causes a change in its electrical resistance. This change in resistance is proportional to the power absorbed by the element. Therefore, the applied power can be measured by monitoring the resistance of the bolometer element.

The bolometer element can be monitored by a balanced bridge circuit, where small resistance changes can be correlated to applied power. The principle of measurement used in the balanced bridge is as follows: The bridge is initially balanced with a DC bias voltage; after balancing, RF power is applied to the bolometer and DC bias is gradually reduced to compensate for the resistance change caused by the RF power, until the bridge is again balanced. Since the initial balance power was equal to the DC power, and the final balance power was a direct result of the RF power, the RF power is equal to the amount the DC bias power was reduced to achieve final bridge balance.

Therefore, if the final DC bias power is subtracted from the initial DC power, the result is the applied RF power:

$RF = P_1 - P_2$
where P_1 is the initial balance DC bias power,
and P_2 is the DC bias power at final balance.

With the preceding principle of balanced bridge power measurement in mind, we will now discuss, in greater detail, the barreter and the thermistor.

630. State the physical and electrical characteristics of the barreter and identify its temperature coefficient.

Barreter. The barreter type of bolometer element uses a metal wire which has a positive temperature coefficient of resistance; that is, the thermal properties of the element are such that with an increase in temperature, the resistance of the element will increase. The resistance of the metal wire is selected to provide the bolometer with a good impedance match to the RF source when biased with DC power. Some barreters consist of encapsulated platinum or resistive coatings on glass or mica. The operating resistance of the barreter is limited to a small range, resulting in a short time constant and correspondingly quick response to changes in power levels. Therefore, it easily follows a modulation envelope, and it is sometimes used as a detector as well as a bolometer.

Exercises (630):

1. The barreter has what type of temperature coefficient?

2. What factor do you take into consideration when selecting the wire for use in a barreter?

3. What characteristic of the barreter makes it useful for tracking a modulation envelope?

631. State the physical construction, electrical characteristics, and precautions you should take with the thermistor.

Thermistor. The thermistor type of bolometer element is normally composed of a ceramic-like mixture of metallic oxides with a large negative temperature coefficient of resistance. In addition, the thermistor element has certain advantages when used in a bolometer mount. It may be operated at relatively high temperatures; it is rugged, both electrically and physically; it has a high resistance to power sensitivity; it can endure large pulse energy; and it has negligible pulse-power measurement error. Along with the aforementioned advantages, some disadvantages are associated with the thermistor. Because of its high temperature coefficient, the thermistor is extremely sensitive to temperature variations and should be thermally shielded and temperature compensated for best results. In addition, the large negative temperature coefficient causes mismatch between the element and the RF source, when large power inputs are applied. Therefore, an attenuator should always be used for high-power measurements to avoid possible damage to the thermistor.

Exercises (631):

1. What materials are used in the construction of the thermistor?

2. What precautions should be observed when using a thermistor for high-power measurements? Why?

632. Compare the operating characteristics of the barreter and the thermistor.

Comparison of Bolometer Elements. The thermistor has a negative temperature coefficient which is ten times greater than that of the positive coefficient barreter, but will not respond so quickly to instantaneous changes in power. The thermistor may also be operated at higher temperatures than the barreter and is more rugged. The barreter is more adaptable to measurements requiring envelope tracking and normally provides better impedance matching characteristics. Because the thermistor is more rugged than the barreter, it is more commonly used in general laboratory applications.

Exercises (632):

1. Match the components in column B with the appropriate construction and operating characteristics in column A. Column B answers may be used more than once.

Column A	*Column B*
____ (1) Quicker response time time operation.	a. Barreter.
____ (2) Better overload and burnout resistance.	b. Thermistor.
____ (3) Positive temperature coefficient.	
____ (4) More sensitive to a power change.	
____ (5) Negative temperature coefficient.	
____ (6) Constructed of a wire or film.	
____ (7) Constructed of small amounts or beads of semiconductor material.	

633. Define the terms "effective efficiency" and "calibration factor," and state their relationship to each other.

Effective Efficiency and Calibration Factor in Bolometer Mounts. Obviously, the accuracy of power measurements using the bolometric method depends largely upon the accuracy of the bolometer element. The accuracy of the element is related, of course, to the amount of the element's resistance changes with a given RF input.

Efficiency. The calibration of a bolometer mount is a highly delicate procedure, involving many sources of error. In practice, the substitution of known RF power levels when performing the calibration of bolometers is rarely used, due to the errors caused by mismatch loss, etc. Instead, a method is used whereby a known DC or audio voltage is applied to the mount, and the power dissipated by the mount is computed from the known voltage and bolometer operating resistance. This method yields fairly accurate results; however, some errors are introduced and must be compensated. These errors are due to the differences in spatial distribution of current, power and resistance within the bolometer element, under RF and DC application.

DC-to-microwave substitution error and RF losses in thermistor mounts are virtually impossible to separate in a quantitative measurement. For this reason, the total effect of these two errors is measured by the National Bureau of Standards (NBS) and some other calibrating facilities and presented as a figure of merit called the effective efficiency (n_e) of the mount.

Effective efficiency of a mount is defined as the ratio of substituted DC power in the bolometer element to the microwave power dissipated within the bolometer mount. This may be stated symbolically as

$$n_e = \frac{P_{DC} \text{ substituted}}{P \text{ microwave dissipated}}$$

and is a ratio less than unity in actual practice, generally expressed in percentage. Note that this expression does not include the effect of mismatch error. Effective efficiency is largely independent of the level of input power; therefore, efficiency test results, for example, at 10 milliwatt are valid at 10 microwatt in well-designed mounts. The effective efficiency data are recorded on the calibration charts or labels for all bolometer mounts calibrated by NBS and AGMC.

Calibration Factor. Calibration data available from NBS, etc., includes another common and very useful term called the calibration factor of the mount. Calibration factor is defined as the ratio of the substituted DC power in the bolometer element to the microwave power incident upon the bolometer mount. This may be stated symbolically as

$$K_b = \frac{P_{DC} \text{ substituted}}{P \text{ microwave incident}}$$

Note that this expression includes the effects of mismatch loss since P_{DC} substituted decreases when RF power is reflected. If a tuner is not used to cancel mismatch effects in a power measurement, calibration factor can be directly applied as a correction to the meter reading to improve overall accuracy. Some of the later generation power measuring devices include the calibration factor and/or effective efficiency as a front panel function, as we shall presently see.

Exercises (633):

1. What ratio is represented by the term "effective efficiency?"

2. What factor, not taken into consideration in the effective efficiency term, is accounted for in the calibration factor term?

3-3. HP–478A Thermistor Mount

As a PME specialist, you will maintain and calibrate many types of bolometer mounts. One such mount is the HP–478A Thermistor Mount. It is a common mount and is used with the HP–432A Power Meter, using the balanced bridge principle discussed earlier. For these reasons, we have included the HP–478A as a representative bolometer mount in this chapter, and will see how the 478A and 432A Power Meter make up a reliable, accurate power measuring system.

634. Specify the operation of the RF and compensation bridges bridges, as used with the HP–478A Thermistor Mount; explain why there are two sets of thermistors; and specify their operating resistance.

Circuit Operation. Figure 3-1 illustrates the simplified circuit diagram of the RF and compensation bridge input circuits. Refer to this figure for the following discussion. There are two pairs of identical thermistors in the HP–478A; one pair for the RF bridge, D_1 and D_2; and one pair for the compensation bridge, C_1 and C_2. Both pairs are mounted on a thermally conductive block, indicated by the shaded area in figure 3-1. Any temperature change felt by one pair of thermistors is felt by the other. The input capacitor, C_2, presents a high impedance to DC and low impedance to the RF component of the input signal.

Prior to the application of RF energy, the thermistor mount is biased automatically by the DC potential at the output of differential amplifier, DA_1, figure 3-1,A. Current flow is from ground through R_{29} and R_{27} to DA_1's output, and through a parallel branch, consisting of the thermistors, D_2 and D_1, and resistors, R_4 and R_5, to DA_1's output. Since these branches are in parallel, the same voltage is applied to each branch. Examination of the resistance values in each branch reveals that when the voltage drop across the thermistors is equal to that across R_{29}, DA_1's inputs are equal, and its output is stable. That output is exactly the voltage required to maintain the resistance of the thermistors, D_1 and D_2, at 200 ohms total series resistance.

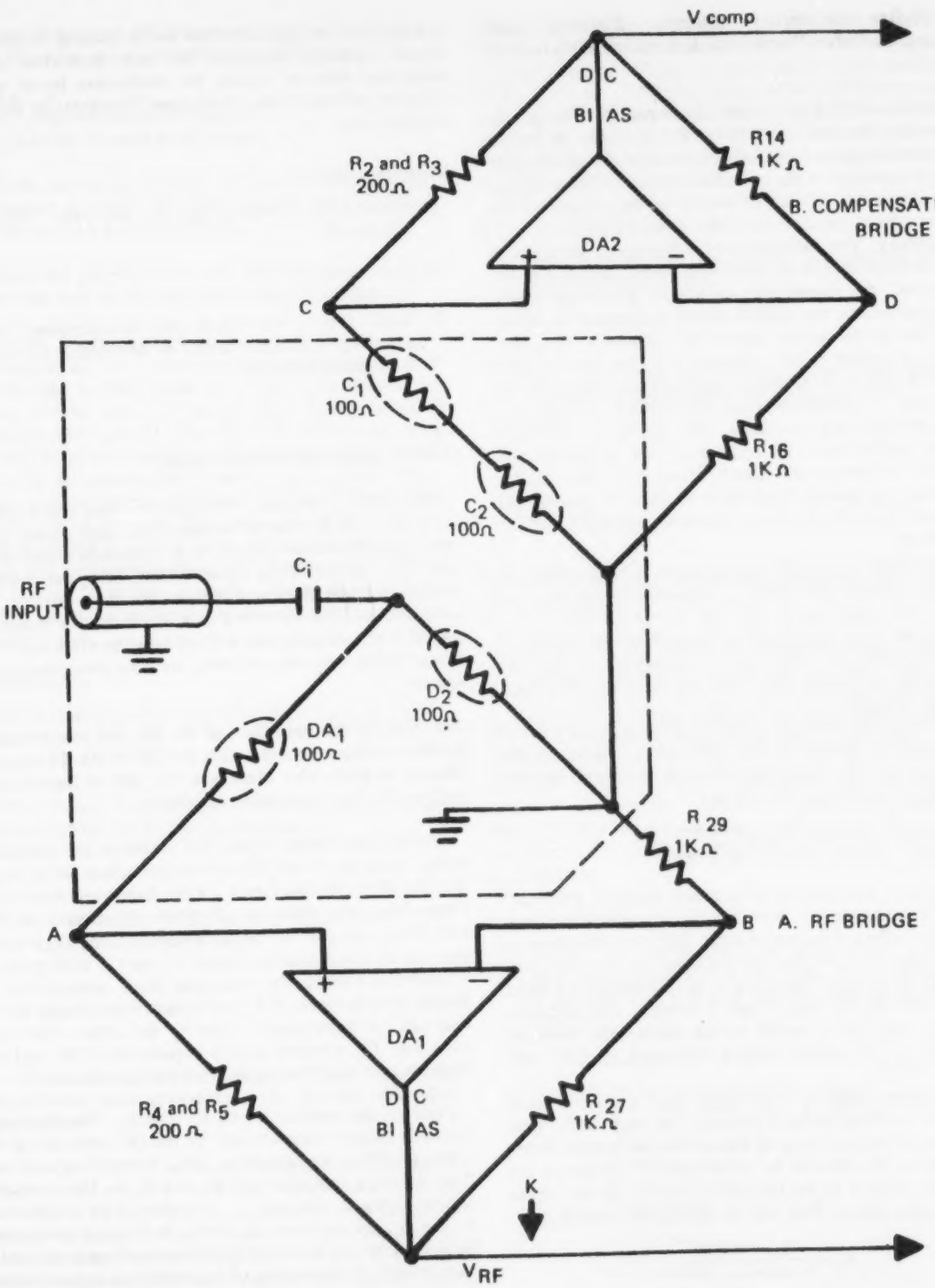


Figure 3-1. Simplified RF and compensation bridge circuits.

If they are not at the proper resistance, the inputs to DA_1 will be unbalanced, and an output will be generated from DA_1, which will be of proper amplitude and polarity to again equalize the input voltages. The compensation bridge circuit in figure 3-1,B is biased in the same manner.

When an RF power level is applied to the RF input of the RF bridge, the resistance of the RF thermistors will decrease. The voltage dropped across them will also decrease, and the inputs to DA_1 will become unbalanced. DA_1's output will decrease, DC current through the thermistors will decrease, and their resistance will increase again until the inputs to DA_1 are equal.

Exercises (634):

1. What is the purpose for having two sets of thermistors in the HP–478 Thermistor Mount?

2. If the temperature surrounding thermistors D_1 and D_2 in figure 3-1,A increases, what will happen to the output of the differential amplifier DA_2 in figure 3-1,B?

3. What is the correct operating resistance of the thermistors in the HP–478A, and how is that resistance maintained?

3-4. HP–432A Power Meter

The HP–432A Power Meter, using temperature compensated thermistor mounts, measures RF power from 10 microwatts (−20 dBm) to 10 milliwatts (+10 dBm) full scale, with 1 percent of full scale accuracy, from 10 MHz to 40 GHz. With a selector switch, the instrument normalizes the power meter reading to compensate for the calibration factor of a thermistor mount used for a given measurement. The 432A has provision for DC substitution measurements and for power meter calibration. An output is provided for recorders or digital voltmeter readout.

635. State the operation of the HP–432A Power Meter, and trace signal flow through its functional blocks.

Operational and Functional Analysis of the HP–432A Power Meter. Figure 3-2 illustrates the front panel of the 432A. Refer to this figure for a discussion of the front panel controls and their functions.

The power (4) switch connects AC line voltage to the internal voltage regulator circuits. Some models of the 432A are equipped with an internal battery supply which this switch connects to the power supply circuits in the ON position. For those models with battery supplies, an optional battery charging circuit operates when AC voltage is being used.

The coarse zero adjustment is adjusted for a zero meter indication with the range (5) selector in the COARSE ZERO position and no RF power applied to the thermistor mount. The fine zero (6) is an electronic zero which balances the compensation bridge with zero RF power input. It is a push-button switch which is depressed momentarily to zero the meter during operation. Be sure that no RF power is applied to the thermistor when the fine zero switch is depressed.

The calibration factor (7) switch is an amplifier gain compensation selector. It is set to correspond to the calibration factor of the thermistor mount being used. The mount resistance (3) selector selects the appropriate resistance for the mount connected to the thermistor mount connector (1) via the proper cable.

The meter and meter zero (2) are similar to other meters you have operated. The meter indicates the power input to the thermistor mount in milliwatts and dBm. To use the dBm scale, algebraically add the full-scale dBm value of the range in use to the meter indication. For example, if the range selector is at 10 dBm and the meter indicates −2 dBm, the RF input to the thermistor is +8 dBm. +10 dBm + (−2 dBm) = +8 dBm. Similarly, if the range is −5 dBm and the meter indication is −3 dBm, the RF input to the mount is −8 dBm. Remember that the range selection dictates the full-scale deflection value. To adjust the meter zero, remove power from the instrument; turn the adjustment screw clockwise until the indicator falls below zero and comes back up to zero again; turn the adjustment very slightly counterclockwise to free the mechanism from the adjusting peg.

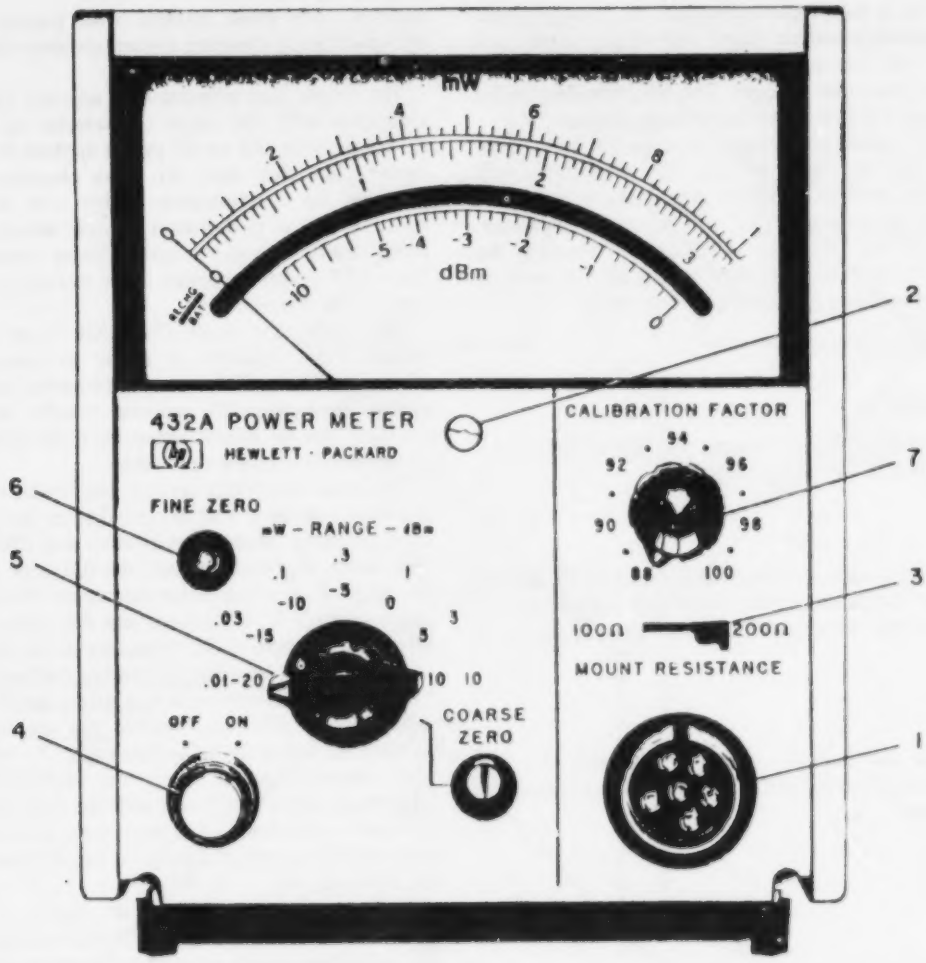
Follow the instructions in figure 3-2 for the preoperational turn-on and zeroing procedures. These are the procedures which must be followed prior to measuring power with the 432A.

Figure 3-3 is the functional block diagram of the HP–432A Power Meter. Refer to the diagram as we trace the signal flow through the power meter.

Generally, the operation of the 432A is as follows. The instrument has two main sections: the bridge circuits and the meter pulse circuits. The bridge circuitry consists of an RF bridge and a compensation bridge, both of which are automatically balanced by feedback amplifiers. The RF bridge is sensitive to input RF power; the compensation bridge compensates for ambient temperature changes.

RF input power is converted to DC power by the input bridges. The DC from the two bridges is summed and subtracted, and the two outputs are chopped at a 5-kHz rate. The subsequent pulses are used in the meter pulse circuits to drive amplifiers that, in turn, drive the meter circuits.

The remainder of the power meter circuitry monitors the output voltages of the bridge amplifiers and reads out the difference between them in terms of incident power to the RF thermistor. Ambient temperature changes cause both thermistors to change resistance similarly, so that there will be no difference in amplifier output voltages. Therefore, any difference in output voltage from the bridges is due to RF power incident to the thermistor mount. Although we



1. Connect the thermistor mount and cable to THERMISTOR MOUNT connector. Refer to Table 1-2 for recommended thermistor mounts and their frequency ranges.
2. Meter Mechanical Zero:
   a. With the instrument turned off, rotate the meter adjustment screw clockwise until the pointer approaches the zero mark from the left.
   b. Continue the clockwise rotation until the pointer coincides with the zero mark. If the pointer overshoots, continue rotating the adjustment screw clockwise until the pointer once again approaches the zero mark from the left.
   c. Rotate the adjustment screw about three degrees counterclockwise to disengage screw adjustment from the meter suspension.
3. Set the MOUNT RES switch to correspond to the operating resistance of thermistor mount used.
4. Turn the 432A POWER switch ON. For battery operation, the AC LINE indicator does not turn on.
5. Set the RANGE selector to COARSE ZERO and then zero the meter with the COARSE ZERO screwdriver adjustment.

   Note

   The power meter should be zeroed with the RF power source turned off, or the mount disconnected from the source.
6. Set the range selector to the 0.01 mW range; then depress the FINE ZERO switch until the meter indicates zero.

   Note

   Range-to-range zero carryover is less than ±0.5% if the meter zero has been adjusted (step 2 above), and the instrument has been properly zero-set on the sensitive range. For maximum accuracy, zero-set the power meter on the range to be used.
7. Set CALIB FACTOR switch to correspond to Calibration Factor imprinted on HP thermistor mount label.
8. Apply RF power to the thermistor mount. Power is indicated on the meter directly in mW or dBm.

Figure 3-2. 432A power meter.

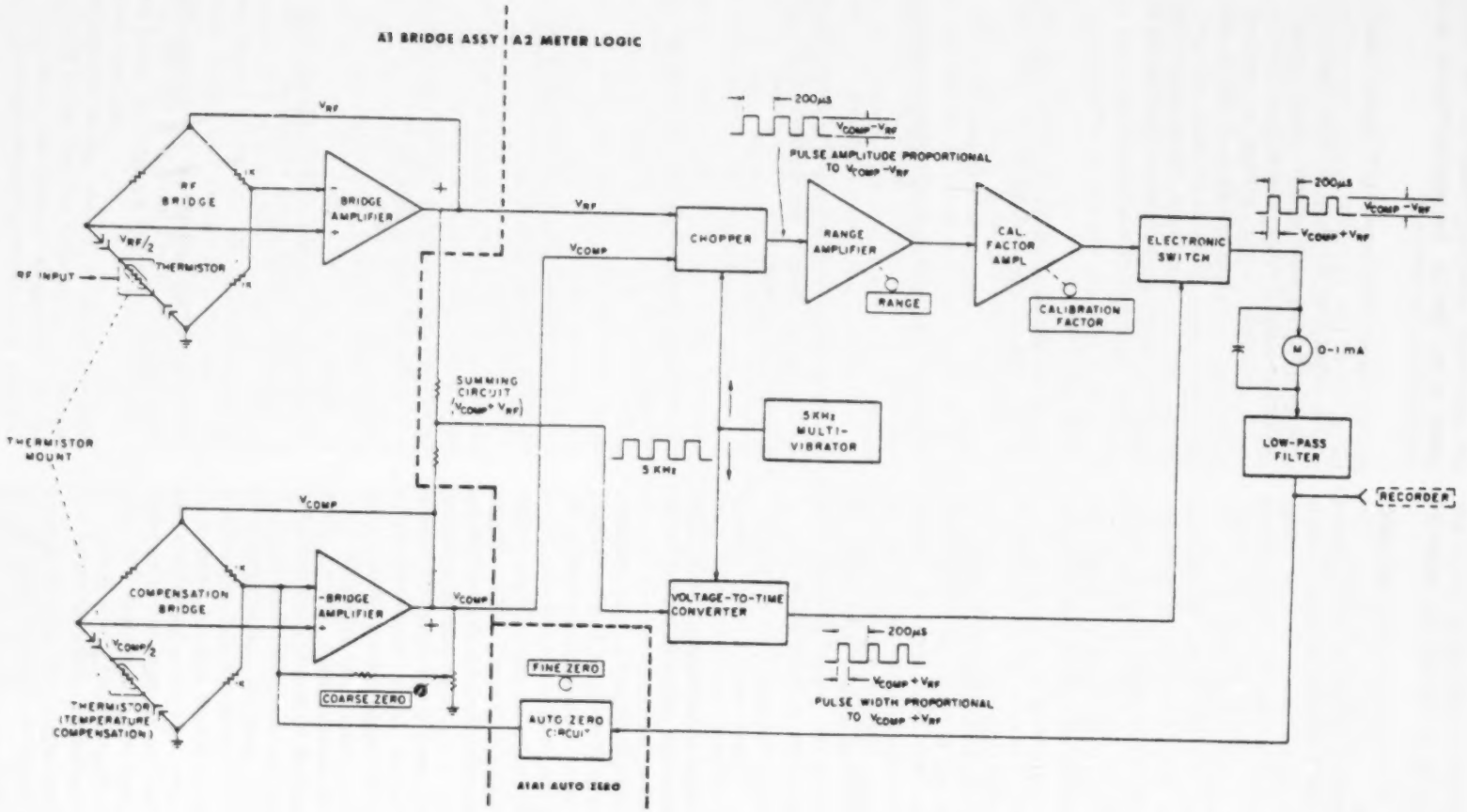


Figure 3-3. 432A block diagram.

discussed the balanced bridge principle earlier, we review the application in this section, so that you may relate the principle to the 432A Power Meter.

The 432A has two thermistors in two automatic, temperature-compensated, balanced bridges. One thermistor measures RF power and the other compensates for ambient temperature variations. Both thermistor mounts are biased with direct current feedback from the bridge amplifiers. Each bridge amplifier supplies enough current to bias the thermistor at exactly 100 or 200 ohms, depending on the mount resistance characteristics.

Each side of the bridge circuit divides the feedback voltage at the top of the bridge by two. If the thermistor resistance changes, then the bridge output voltages are not equal, and the bridge amplifier amplifies the difference and returns the correction voltage to the top of the bridge. The new voltage changes the thermistor current. The thermistor resistance will change to compensate for original variation. This way, the bridge feedback ensures that the thermistor is always operating at a constant resistance.

The voltage at the top of the RF bridge is dependent on both ambient temperature and RF input. The voltage at the compensation bridge is dependent only on ambient temperature. If the RF thermistor receives any RF power, its temperature will change, which changes the operating resistance, which, in turn, unbalances the bridge. The differential amplifier senses the bridge unbalance, and returns a correction voltage to the top of the RF bridge.

The outputs of the differential amplifiers are routed to two circuits—a 5-kHz chopper circuit and a voltage summing circuit. These outputs represent the RF input power and the ambient temperature compensation voltage, V_{RF} and V_{COMP}, respectively. The output from the summing circuit is a voltage which represents the sum of V_{RF} and V_{COMP}. This sum voltage is fed to a voltage-to-time converter whose output will be a 5-kHz, rectangular waveform, and whose pulse width is proportional to the sum of V_{RF} and V_{COMP}. A 5-kHz, multivibrator circuit controls the output frequency of the voltage-to-time converter and the chopper frequency. The chopper alternately samples the outputs of the differential amplifiers, and its output is a symmetrical square wave, whose amplitude is proportional to the difference between V_{RF} and V_{COMP}. The chopper output is amplified by an amount determined by the range setting of the range selector switch and by the setting of the calibration factor switch. After amplification, the pulses are fed to an electronic switch. The switch is turned on by the output pulses from the voltage-to-time converter. These pulses are rectangular and slightly narrower than the pulses from the amplifiers. The output from the switch, then, is a rectangular pulse, whose amplitude is proportional to the difference, and whose pulse width is proportional to the sum of V_{RF} and V_{COMP}. Note that the amplitude of the pulses will be zero when V_{RF} and V_{COMP} are equal. The pulse width, proportional to $V_{RF} + V_{COMP}$, is always 90 microseconds or less in length at a frequency of 5 kHz.

The meter is 0-1 mA, full-scale meter that has a capacitor connected across its terminals. The capacitor integrates the output pulses from the electronic switch circuit, so that the current into the meter is proportional to time average of th input pulses. That is, the input current to the meter i proportional to the product of

$$(V_{COMP} + V_{RF})(V_{COMP} - V_{RF}) = (V_{COMP})^2 - (V_{RF})^2.$$

The output from the meter is further filtered so that th voltage at the rear panel recorder output is suitable for us with either a digital voltmeter or an X–Y recorder.

The recorder output voltage is returned to th compensation bridge through a feedback circuit. Th feedback circuit, which is the auto zero and memor circuit, holds a correctional voltage at the input of th compensation bridge amplifier, so that when the RF input i zero, the meter indication will also be zero.

Exercises (635):

1. What precaution should be followed when fine zeroin the HP–432A Power Meter?

2. What is the function of the calibration factor switch?

3. If the 432A range selector is at 5 dBm, and the mete indicates −2 dBm, what is the input RF power at th thermistor mount?

4. What is represented by the 5-kHz chopper output in th 432A?

5. What is represented by the output of the voltage-t time converter in the 432A?

6. What signal controls the on-off operation of th electronic switch in the 432A?

7. What is the purpose of the capacitor across the mete movement terminals?

8. What is the purpose of the low-pass filter outpu voltage?

636. State how to solve problems concerning the thermistor bridge circuits of the HP–432A Power Meter.

Thermistor Bridge. The thermistor bridge (see fig 3-4) consists of the thermistor(s), R29, R27, and R5 (R4 and R5 for 200-ohm thermistor resistance). The mount resistance selector maintains bridge balance for 100-ohm or 200-ohm thermistors. The bridge output goes to Q12A/B from across the RF thermistor and R29, respectively. The circuit output (V_{RF}) is taken from the center of S3. As RF input power increases, the thermistor resistance decreases, decreasing V_{RF}. Q12A/B amplify the voltage difference between the two sides of the bridge. Q13 is a high-impedance current source for high-amplifier common-mode rejection. R15 is a balance potentiometer to equalize the base voltages of Q12A and B. C6 and C11 are for noise filtering. The dashed lines around the base circuits of Q12A and Q12B represent guard rings which protect the base circuits from leakage currents across the circuit board. Q9 and Q10 make up another differential amplifier which amplifies the voltage difference between the collectors of Q12A and Q12B. Q15 and Q11 supply bias current to the bridge circuit to maintain correct thermistor resistance. RF power to the thermistor decreases its resistance. Q11 then supplies less current to compensate. Q15 provides current gain to drive Q11.

Assume the bridge to be in a balanced condition, with no RF input to the thermistor mount. The DC current through the bridge and, consequently, through Q11 is stable and is of the precise value to maintain the thermistor at 200 ohms (in case of the HP–478A Thermistor Mount). When an RF power level is applied, the resistance of the thermistor decreases, decreasing the voltage dropped across it and the voltage felt at the base of Q12A. Q12A is an NPN transistor whose forward bias will decrease with the decreasing voltage on its base. Its collector will then rise due to decrease current flow, and the emitter potential will decrease. The negative-going emitter potential of Q12A is felt on the emitter of Q12B. The base of Q12B is tied to the top of the thermistor bridge and to the collector of Q11, which feels little or no change in potential at this time. The collector voltage of Q12B will decrease due to the increase in forward bias and subsequent current flow. The base of Q9 feels the positive-going voltage from the collector of Q12A, and its emitter will also begin to rise. The emitter of Q10 feels the same positive-going potential. Q10's base is tied to the collector of Q12B, which is decreasing in potential. Q10 is now reverse biased, and its collector potential rises. This positive going voltage at the base of PNP transistor Q15 reverse biases it, and its collector voltage rises, reverse biasing Q11. DC current flow through the thermistor bridge and through Q11 decreases. The decreased DC current flow through the thermistor allows its resistance to rise until it is of the correct value and again balances the bridge. Note that the voltage (V_{RF}) at the top of the bridge has decreased.

The compensation bridge operates in almost the same manner as the RF bridge. The thermistor resistance changes only as a function of the ambient temperature and the remainder of the bridge-balancing process is as described for the RF bridge. Later in this section, we will discuss the automatic zero and FET memory circuits.

Exercises (636):

1. How will current flow through Q11 be affected if the RF power level to the thermistor decreases?

2. If the ambient temperature at the thermistor mount increases, what will happen to the potential at the base of Q4?

3. What will be the effect on V_{RF} if the R29 is shorted?

4. What will be the effect on V_{RF} if the RF thermistor is shorted?

5. How will shorting R8, the emitter resistor of Q4 and Q5, affect V_{COMP}?

637. Identify specified conditions in the meter logic circuits of the HP–432A Power Meter.

Meter Logic Circuits. Figure 3-5 illustrates the meter logic circuits of the HP–432A. Follow this circuit during the following discussion.

Q22 and Q23 form an astable 5-kHz multivibrator. Its output is a 7 volt square wave. Q22 and Q23 saturate, but do not cut off. The outputs of the multivibrator are 180° out-of-phase and are used to drive the rest of the meter logic switching circuits.

Nonlinear amplifiers Q21 and Q24 are driven from cutoff to saturation by the multivibrator. CR11 and CR12 clamp the maximum positive output levels from the amplifiers to zero volts.

V_{COMP} and V_{RF} are summed at the function of R78 and R79. The output voltage (with respect to ground) equals 1/2 (V_{COMP} + V_{RF}). The ground connection through S3 (at 200 ohms) compensates for the greater output voltage of the bridges when used with 200-ohm thermistor mounts.

Assume again that the RF bridge is initially balanced, with no RF input. Also, assume that the collector of Q23 is high (−6V) and that the collector of Q22 is low (−13 volts). Q24 is saturated by the high at its base; therefore, its collector is at maximum negative potential (−13 volts). Q24's collector voltage is coupled to the gate of Q30. Q21, which is cut off by the low collector voltage of Q22, has a maximum high collector voltage of 0 volts. This potential is coupled to the gate of Q32. This combination of outputs

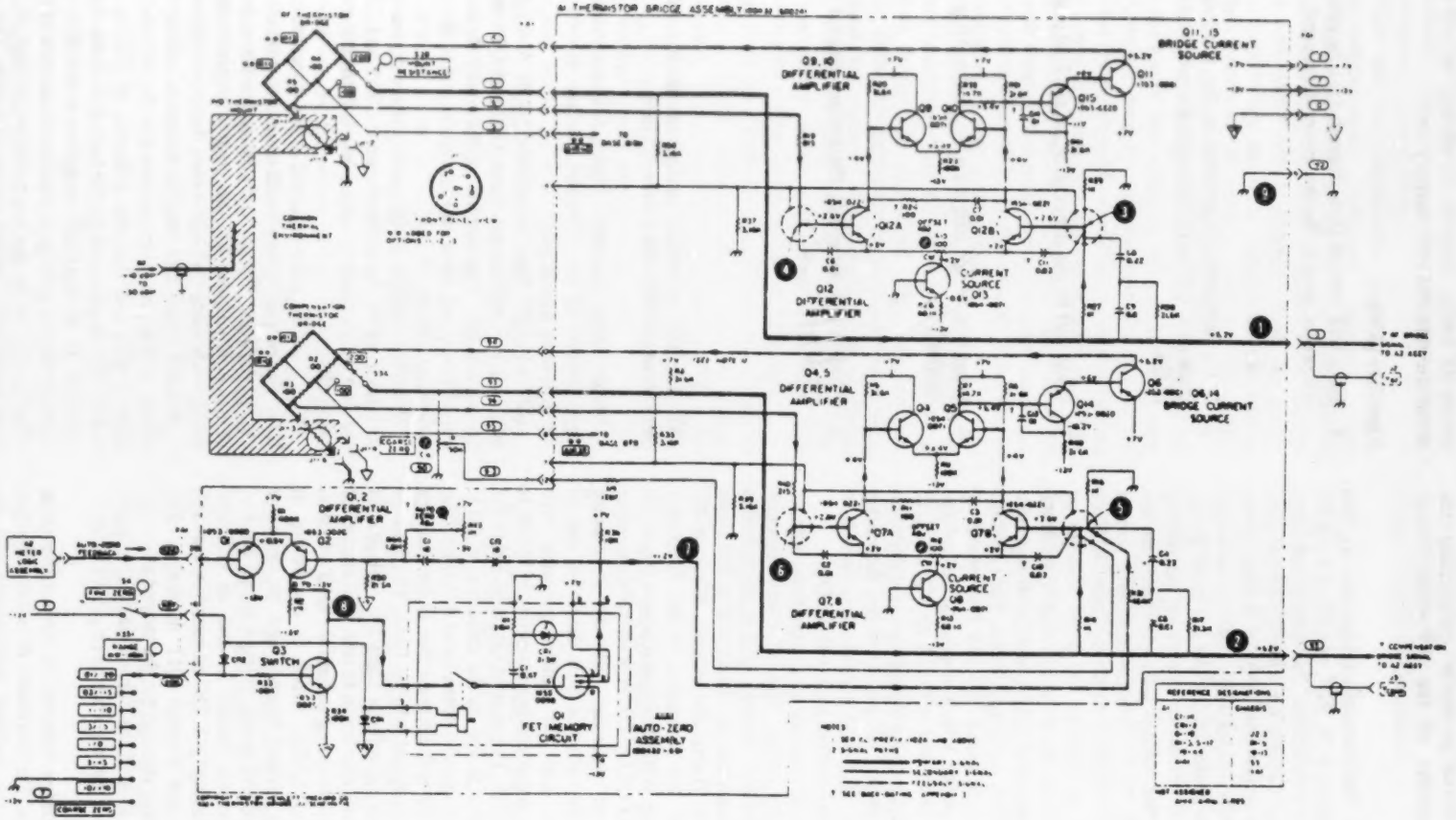


Figure 3-4. 432A RF bridge.

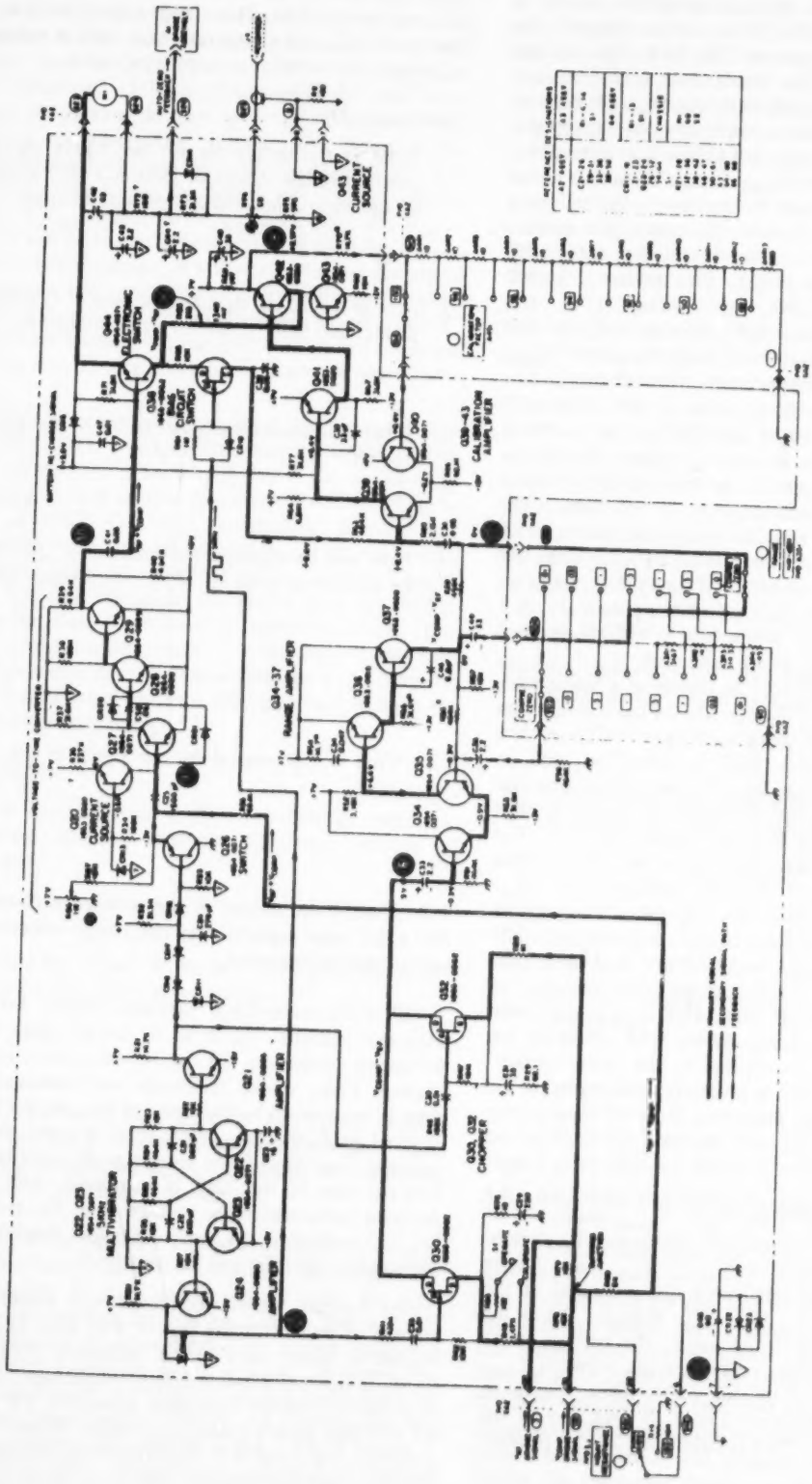


Figure 3-5. 423A meter logic.

from the multivibrator and nonliner amplifiers results in forward bias on Q32. FET Q30 is reverse biased. The source of Q32 is tied to the output of the RF bridge, and that potential represents V_{RF}. The output from Q32 then, is a positive pulse, whose amplitude represents V_{RF}. On the next alternation of the multivibrator, the biasing of the chopper FETs is reversed, and the output of Q30 is a positive going waveform which represents V_{COMP}. Since the outputs of the chopper FETs are referenced to the same potential, and since they are 180° out-of-phase, their resultant outputs represent $V_{COMP} - V_{RF}$. In a balanced condition, with no RF input, V_{RF} and V_{COMP} are equal. This reference is felt through the range amplifier, Q34 through Q37, and calibration factor amplifier, Q39 through Q42, to the collector of Q44. Recall that this voltage represents $V_{COMP} - V_{RF}$, with no RF input power, a zero reference level.

The 5-kHz output from the collector of Q21, 0 to −13 volts, is applied through CR16 and CR17 to the anode of CR18. When this signal is maximum positive (0 volts), a positive signal is developed at the base of Q26. When Q21's output is maximum negative (−13 volts), the potential at Q26's base is zero. A voltage representative of $V_{RF} + V_{COMP}$ is applied to the emitter of Q26 from the summing junction of R78 and R79. When Q26 is turned on by the positive pulse on its base, its emitter potential is at a virtual ground, zero volts. When Q26 is off, the emitter potential will be a voltage which represents $V_{RF} + V_{COMP}$. Current source Q20 forces C25 to charge at a linear rate. When Q26 is off, C25 will charge toward the signal at the emitter of Q26. When the charging voltage of C25 reaches approximately −12.4 volts, Q27 is turned on, and its emitter-base current clamps the collector of Q20 to that voltage. When Q26 is turned on again, its emitter voltage drops to zero, discharging C25 and turning Q27 off. The charge time of C25 is dependent upon the value of the bridge input voltages. If the RF bridge input (V_{RF}) increases, the length of time that C25 takes to charge to −12.5 volts, the turn on voltage of Q27, will decrease. Q27 will be turned on for a longer length of time, and its turn-off time will decrease. The positive pulse at the collector of Q29 is equal to the turn-off time of Q27. It is this pulse which turns on the electronic switch Q44, allowing the $V_{COMP} + V_{RF}$ term to be applied to the meter circuit. Remember that the V_{RF} term is inversely proportional to the amplitude of the RF input. Therefore, if the RF input power level increases, the V_{RF} term will decrease. Q27 will be cut off longer, and the switch Q44 will be open for a longer length of time.

Q44 will be turned off by the $V_{RF} + V_{COMP}$ pulse, and its emitter output will be a rectangular, positive pulse, whose pulse width is proportional to $V_{RF} + V_{COMP}$, and whose amplitude will be dependent upon the potential at the collector of Q44, the $V_{COMP} - V_{RF}$ voltage. When the bridge is balanced, with no RF input, the voltage at the collector of Q44 represents a zero difference between V_{COMP} and V_{RF}. The voltage at the top of the meter circuit is proportional to the collector voltage of Q44 and to the length of time in which Q44 is held open by the positive pulse on its base.

Bias circuit switch Q38 conducts when Q44 is turned off. Any residual current flowing from Q42 (in excess of that current drawn by current source Q43) is shunted through Q38 and charges C38. This charge adjusts the bias on Q39, Q41, and Q42, and the current from Q42 is reduced. This adjustment provides for good zero carryover.

Exercises (637):

1. What is the amplitude of the 5-kHz signal at the junction of the drains of Q30 and Q32 when the RF bridge input equals the compensation input?

2. How is the 5-kHz signal at the base of Q34 affected by an increase in RF power to the thermistor mount?

3. What determines the pulse width of the signal at the collector of Q29?

4. How will the signal at the collector of Q29 be affected by a decrease in the RF input to the thermistor mount?

5. What is represented by the signal at the emitter of Q44?

638. Specify the action of the auto-zero circuits of the HP–432A, and explain why the range selector is in the coarse zero adjustment.

HP–432A Auto–Zero Circuits. Figure 3-4 shows the auto-zero circuits. Refer to it and to figure 3-5 for the following discussion. Q1, in the auto-zero circuit, is a P-channel FET, whose resistance and consequent voltage drop is determined by the value of the gate voltage. In a P-channel FET, the gate is made of N-type semiconductor material; therefore, if the gate is made more negative, the forward bias of the FET is increased, with a resulting decrease in resistance and voltage drop. The gate voltage of Q1 is controlled by the collector potentials of Q2 differential amplifier and the switch Q3.

Any upscale meter indication will cause a positive voltage to be felt at the top of R73 (see fig. 3-5). This voltage is routed back to the thermistor bridge assembly shown in figure 3-4 and is applied to the base of differential amplifier Q1, on the thermistor assembly. The collector of Q2 will also go in a positive direction. When the fine zero switch is depressed, K1 is energized by a negative 13-volt potential, and the collector voltage of Q2 is applied to the gate of FET Q1 on the auto-zero assembly. This positive-

going voltage decreases the forward bias of the FET, increasing its resistance and corresponding voltage drop. The increased voltage at the source terminal of the FET is felt at the base of Q7B, whose collector will go in a negative direction. Q5's collector potential will rise, decreasing conduction through Q14. The emitter of Q14 will feel a positive-going voltage and decrease the conduction through Q6 and the compensation bridge. The voltage drop at the top of the bridge will decrease and be felt at the V_{COMP} output. If V_{COMP} decreases, the V_{RF} + V_{COMP} term will decrease; the amplitude of the pulse applied to the meter will decrease, as will the voltage at the top of R73. The meter will now indicate a zero RF input, and the input to the auto-zero circuits will decrease to zero volts. C_1 in the FET circuit charges to the gate voltage and keeps the FET gate at the correct potential to maintain zero meter indiction.

When coarse zeroing the meter, place the range switch in the COARSE ZERO position. This switch position applies −13 volts to the base of switch Q3 and to the coil of relay K1. K1 energizes and applies the collector voltage of Q3 to the fate of FET Q1. Q3, conducting heavily has approximately −6.5 volts on its collector. This −6.5 volts is at the approximate center of FET Q1's operating voltage. As in the fine zero operation, the output from the FET is applied to the base of differential amplifier Q12B. The remainder of the circuit operation is the same as for fine zeroing. The coarse zero control adjusts the V_{COMP} term for a zero meter indication while the FET memory circuit is set at its center operating voltage.

Exercises (638):

1. Specify the action of FET Q1, when the meter is indicating upscale, and the fine zero switch is depressed.

2. Why must the range selector be in the COARSE ZERO position for the coarse zero adjustment?

639. Specify the basic reference for the power supply circuits of the 432A Power Meter; explain how base voltage of Q8 is affected by +7 increase; and indicate how Q2 is protected from overcurrent.

HP–432A Power Supply. The power supply, shown in figure 3-6, is a fairly conventional supply. The outputs are regulated negative 13 volts and positive 7 volts, the −13 volt supply referenced to the +7-volt supply. The +7-volt supply is referenced by zener diode CR6, which maintains the emitters of Q3 and Q4 at −6.3 volts. Q6 keeps the emitters of Q5 and Q6 at a slightly positive potential with respect to the power supply ground and compensates for temperature changes. Any change in the +7-volt output is felt at the wiper of R6, through Q5, amplified by Q4 and Q1, and fed to the base of series regulator Q2. The output of Q2 controls current through the various branches of the power supply and keeps the voltage difference between the supply output terminals at nominally 20 volts. Q11 is a current switch. When the current through R2 and Q2 exceeds about 90 mA, the voltage drop across R2 will cause Q11 to turn on and shunt a portion of the current.

If the +7-volt supply increases, a corresponding increase in the voltage drop across R13 will occur. This positive-going voltage decreases forward bias on Q7. The collector voltage of Q7 will decrease and decrease forward bias on Q8, whose collector potential will increase. The increasing voltage at the collector of Q8 is felt on the bases of Q9 and Q10. Q9's forward bias will increase and Q10's forward bias will decrease. The collector of Q9, tied to the +7-volt output through R17, will decrease to +7-volts. The −13-volt supply functions in somewhat the same manner. An increase of the −13-volt output (going more negative) results in a lower potential at the top of R13, although the current has increased slightly. Q7 conducts harder, its collector voltage increases, increasing forward bias on Q8. Q8's collector voltage decreases, causing Q10's collector voltage to rise. Q10's collector is tied to the −13-volt output through R18. The −13-volt output will follow the collector of Q10 and rise to the correct value.

Exercises (639):

1. What provides the basic reference for the HP–432A power supply output voltages?

2. How will the base voltage of amplifier Q8 be affected by an increase in the +7-volt output?

3. How is series regulator Q2 protected from overcurrent?

3-5. AN/UPM–144 Pulse Power Test Set

The Pulse Power Test Set, AN/UPM−144 is a laboratory standard utilized at intermediate level to facilitate testing and calibration of IFF and TACAN test equipment. The test set generates pulsed radio frequency signals that duplicate IFF interrogator output signals. Intermediate maintenance level technicians employ those test signals to calibrate the IFF test equipment to specified tolerances. In addition to generating IFF signals, the test set is capable of generating pulse characteristics and spacing of TACAN equipment within the operating frequency range of 1024 to 1151 megahertz.

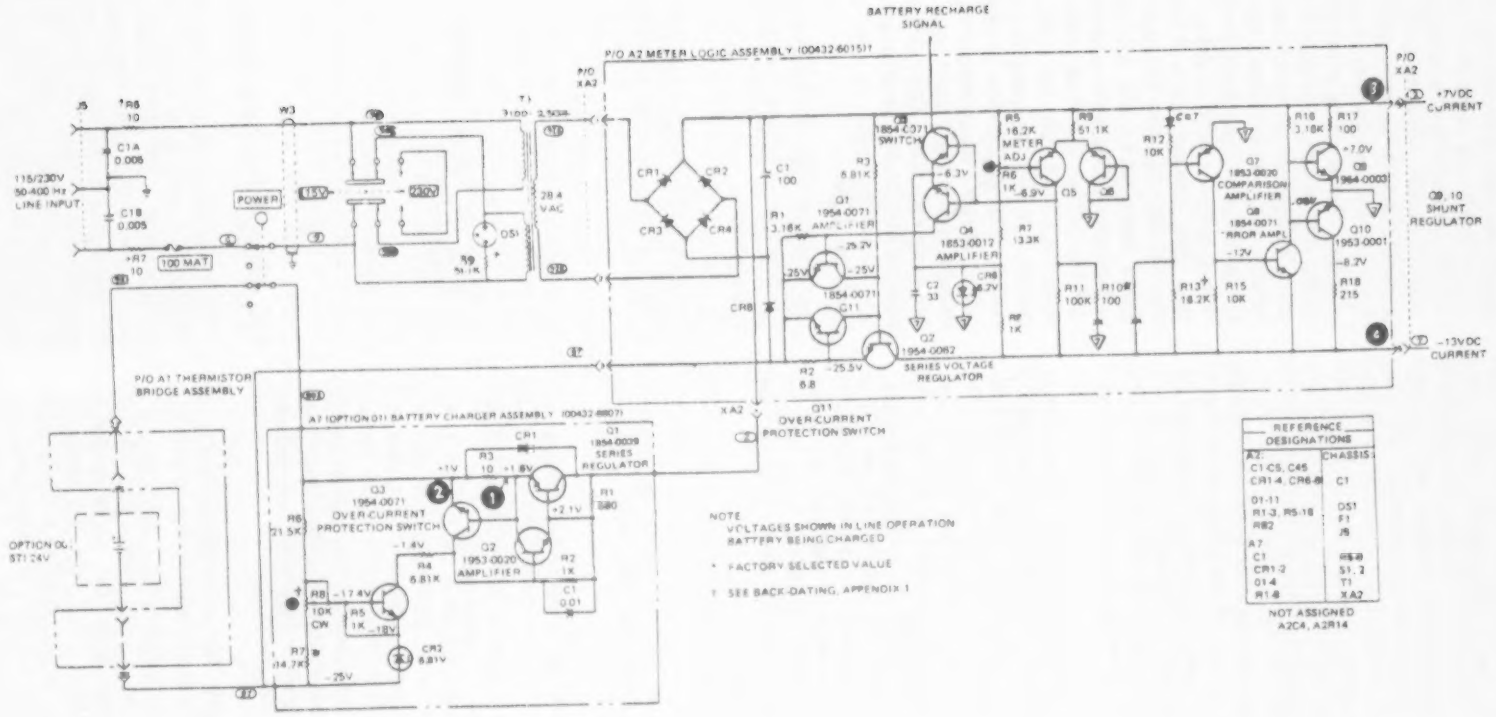


Figure 3-6. 422A power supply.

640. State the purpose and uses of the AN/UPM-144 Test Set.

Purpose and Use of Equipment. The test set is a pulse-power device capable of generating high power IFF or TACAN coded RF pulses of the necessary shape and duration. In addition, low power IFF pulse groups can be generated, including a separately adjustable side lobe suppression (SLS) pulse. The RF frequency of these pulses is highly stable and accurate, since they are derived from a crystal oscillator through phase-lock technique. Selected frequency is displayed directly on a digital readout in the right upper corner of the test set front panel. At high power levels, amplitude accuracy of the RF output signal is achieved through use of an internal peak power meter circuit which provides a highly accurate peak power indication on a front panel meter movement; at low power levels, amplitude accuracy is obtained by means of internal RF leveling and the use of individually calibrated precision variable attenuators. In the video section, pulse width and spacing are digitally controlled from a crystal clock and are adjustable to precise values by means of front-panel thumbwheel switches.

Provision is made for external synchronization of the test set and for external pulse modulation of the low-level RF, via a front panel sync select switch and associated connectors. A video monitor output jack is provided for the low power signals, and a low power CW RF output is available for test purposes.

Exercises (640):

1. State the purpose of the UPM-144.

2. How are highly stable and accurate pulses derived in the UPM-144?

3. The test set UPM-144 can be used to test and calibrate what type of equipment?

3-6. The HP-8481A Power Sensor

The modern thermocouple is exemplified by the HP 8481A Power Sensor, which has taken advantage of both semiconductor and thin-film technologies. A thin-film resistor, constructed of tantalum-nitride and deposited on the surface of a silicon chip, converts the microwave energy to heat. The tantalum-nitride resistive material forms a low-reflection termination for the RF transmission line to frequencies above 18 GHz. Yet the resistor is not at all fragile in contrast to similar terminations constructed of a highly conductive material like most metals. It is largely because of this thin-film resistor that the thermocouple sensor has the lowest reflection coefficient of all the sensing methods.

641. State the operating properties of the HP 8481A Power Sensor.

Power Sensor Properties. The 8481A thermocouple consists of a silicon chip with several other materials deposited on top as shown in figure 3-7. Each chip actually contains two thermocouples but this discussion will concentrate on only one for a moment. The tantalum-nitride resistor, for converting the RF energy into heat, is deposited on top of the silicon. A silicon-dioxide insulating layer separates the resistor from the silicon. At one end of the resistor, the end near the center of the chip, the insulating layer has a hole through which the resistor is connected to the silicon. The other edge of the resistor and the far edge of the silicon chip have gold beam-lead contacts. The beam leads not only make electrical contact to the external circuits, but also provide mounting surfaces for attaching the chip to a substrate, and serve as thermal paths for conducting heat away from the chip.

As the resistor converts the RF energy into heat, the center of the chip, which is very thin, gets hotter than the outside edge for two reasons. First, the shape of the resistor causes the current density and the heat generated to be largest at the chip center. Second, the outside edges of the chip are thick and well cooled by conduction through the beam leads. Thus there is a thermal gradient across the chip which gives rise to the thermoelectric emf. The hot junction is the resistor-silicon connection at the center of the chip. The cold junction is formed by the outside edges of the silicon chip and the resistor. The cold junction is separated to form the two contacts to external circuitry.

The HP-8481A Power Sensor contains two identical thermocouples on one chip, electrically connected as in figure 3-8. The thermocouples are connected in series as far as the DC voltmeter is concerned. For RF frequencies, the two thermocouples are in parallel, being driven through coupling capacitor C_c. Half the RF current flows through each thermocouple. Each thin-film resistor and the silicon in series with it has a total resistance of 100 ohms. The two

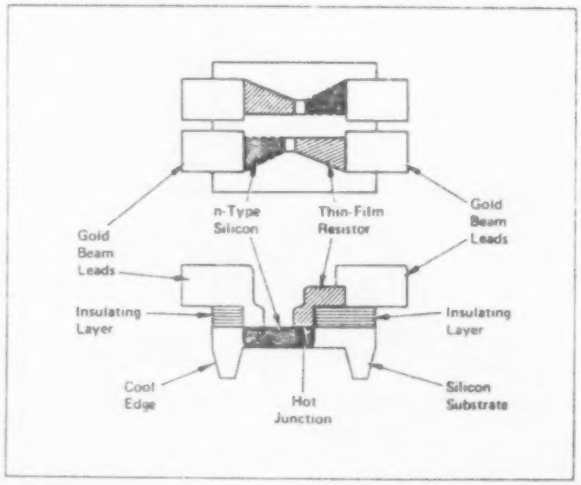


Figure 3-7. Structure of the HP-8481A thermocouple chip.

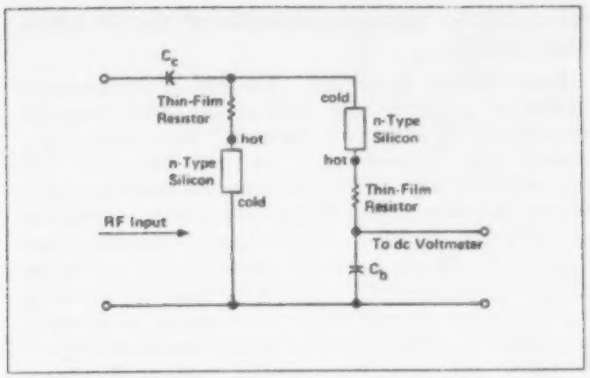


Figure 3–8. Schematic diagram of the HP–8481A thermocouple power sensor.

thermocouples in parallel form a 50 ohm termination for the RF transmission line. The lower node of the left thermocouple is directly connected to ground and the lower node of the right thermocouple is at RF ground through bypass capacitor C_b. The DC voltages generated by the separate thermocouples add in series to form a higher DC output voltage. The principle advantage, however, of the two thermocouple scheme is that both leads to the voltmeter are at RF ground; there is no need for an RF choke in the upper lead. If a choke were needed it would limit the frequency range of the sensor.

The thermocouple chip is attached to a transmission line deposited on a sapphire substrate as shown in Figure 3-9. Coplanar transmission line is used to allow the line dimensions to taper down to the chip size, while still maintaining the same characteristic impedance in every cross-sectional plane. This structure contributes to the very low reflection coefficient of the 8481A sensor, especially at microwave frequencies.

The principle characteristic of a thermocouple sensor for high frequency power measurement is the sensitivity in microvolts output per milliwatt of RF power input. The sensitivity is equal to the product of two other parameters of the thermocouple, the thermoelectric power and the thermal resistance.

The thermoelectric power (not really a power but physics texts use that term) is the thermocouple output in microvolts per degree centigrade of temperature difference between the hot and cold junction. In the HP 8481A thermocouple mount, the thermoelectric power is designed to be 250 μV/°C. This is controlled by controlling the density of n-type impurities in the silicon chip.

The thickness of the HP-8481A silicon ship was selected so the thermocouple has a thermal resistance 0.4°C/mW. Thus the overall sensitivity of each thermocouple is 100 μV/mW. Two thermocouples in series, however, yield a sensitivity of only 160 μV/mW because of coupling between the thermocouples; the cold junction of one thermocouple is heated by the resistor of the other thermocouple giving a somewhat smaller temperature gradient.

The thermoelectric voltage is almost constant with temperature. It depends mainly on the temperature gradients and only slightly on the ambient temperature. Still, ambient temperature variations must be prevented from establishing gradients. The chip itself is only 0.8 mm long and is thermally short-circuited by the relatively massive sapphire substrate. The entire assembly is enclosed in a copper housing. Figure 3-10 depicts the better thermal behavior of a thermocouple compared to a thermistor power sensor.

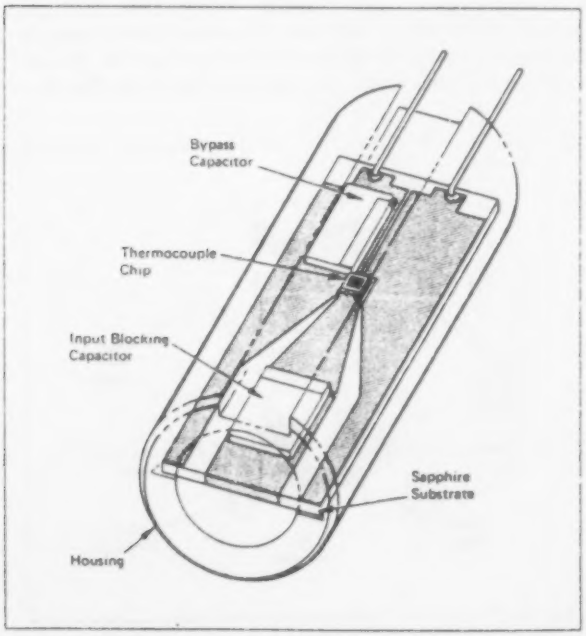


Figure 3–9. Sketch of the thermocouple assembly for the HP–8481A.

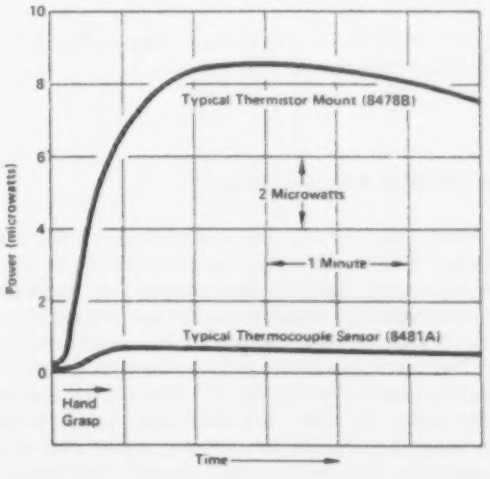


Figure 3–10. Zero drift of thermocouple and thermistor power sensors due to being grasped by a hand.

The thermoelectric power is not exactly constant, but does vary somewhat with temperature. At large powers, where the average thermocouple temperature is raised, the output voltage is larger than predicted by extrapolating data from low power levels. At a power level of 30 mW the output is 3 percent high, at 100 mW it is about 10 percent high. The circuitry in the HP power meters used with thermocouples compensates for this effect. Circuitry in the sensor itself compensates for changes in ambient temperature.

The thermal resistance limits the maximum power that can be dissipated. If the hot junction rises to 500°C, differential thermal expansion causes the chip to fracture. The HP-8481A is limited to 300 mW maximum average power.

The thermal resistance combines with the thermal capacity to form the thermal time constant of 120 microseconds. This means that the thermocouple voltage falls to within 37 percent of its final value 120 µs after the RF power is removed. The response time for measurements, however, is usually much longer because it is limited by noise considerations in the voltmeter circuitry.

The only significant aging mechanism found so far is thermal aging of the tantalum nitride. A group of devices were stress tested, producing the results of figure 3-11. These curves predict that, if a device is left at 300 mW for 1 year, the resistance should increase by about 3.5 percent. Nine days at a half watt would cause an increase in resistance of 2 percent. The aging accumulates.

With such a design it is relatively easy to adapt the basic design to other requirements. It is easy, for example, to change each tantalum-nitride resistor to 150 ohms so that the thermocouple can work in 75 ohm systems. It is also easy to enhance low frequency performance by using larger blocking and bypass capacitors. This usually compromises high frequency performance due to increased loss and parasitic reactance.

Exercises (641):

1. What component in the 8481A Power Sensor converts the RF energy into heat?

2. The HP 8481A Power Sensor contains how many thermocouples?

3. As far as DC is concerned, how are the thermocouples of an HP 8481A connected?

4. What is the principle characteristic of a thermocouple sensor for high frequency power measurements?

3-7. Network Analyzer (8410A, 8411A, 8413A)

The network analyzers are used to measure phase angles and amplitude ratios. There are three specific models: 8410A, 8411A, and 8413A discussed.

642. State the purpose of the Model 8410A Network Analyzer and the 8411A Frequency Converter and their operating precautions.

Instrument Measurement. The combination of Model 8410A Network Analyzer, Model 8411A Frequency Converter, and a display unit for the Model 8410A function as a phasemeter and a ratiometer for direct, continuous, simultaneous phase and amplitude ratio measurement on RF voltages. The complete instrument measures phase angles from 0 to 360° and amplitude ratios in decibels over a dynamic range of 60 dB. These measurements can be made on single frequencies and on swept frequencies in overlapping octave bands from 110 MHz to 12.4 GHz.

Measurements possible with the network analyzer include: direct determination of scattering(s) parameters; swept-frequency response measurements of phase sensitive systems; analysis of parameters relating to the use of solid state devices in wideband circuits; group delay measurements for communications systems; analysis of phase distortion in filters, amplifiers, and preamplifiers; antenna testing; and performance testing of components of sophisticated radars. Although the network analyzer is intended primarily for wideband coaxial measurements, it can also be used with waveguides within the limits imposed by waveguide bandwidths and the characteristics of waveguide-to-coax adapters.

The Models 8410A and 8411A convert the two RF signals being measured to two 278–kHz signals that have the same relative amplitudes and phase. The phase and amplitude information provided by the display unit used with the Model 8410A is derived from these 278-kHz signals. External monitoring points for the 278-kHz signals are provided on the Model 8410A. Operating power for the display unit and for the Model 8411A is furnished by the Model 8410A.

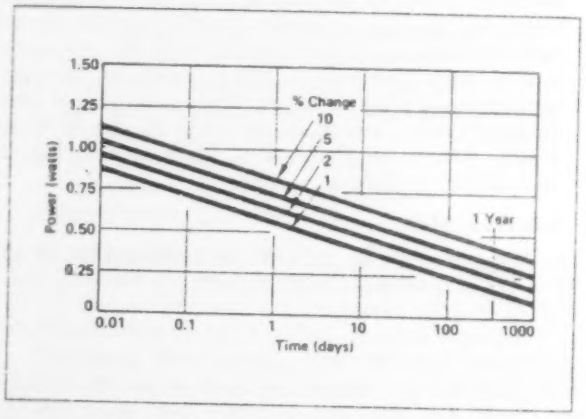


Figure 3–11. Results of step stress aging test.

The Model 8411A automatically tracks the frequency of the signal applied to the reference input. This automatic tuning and tracking takes place over the octave frequency band preselected by a front panel control. In addition to the band selector, there is a control that permits the search and hold range of the automatic tuning to be adjusted for best performance with the selected band. For swept-frequency measurements at faster rates, a rear-panel input accepts a sweep reference voltage proportional to the frequency of the input signals.

The signal applied to the reference input of the Model 8411A is used as the reference for both phase and amplitude measurements. Since it actuates the automatic tuning, its level is critical. A meter on the Model 8410A continuously monitors the reference channel signal level and indicates whether it is in the range required for making measurements.

Controls on the Model 8410A include phase and precision step-action amplitude offset controls. The vernier controls are for convenience in setting reference and calibration phase and amplitude indications. The amplitude offset controls allow large amplitude differences to be measured with greater resolution.

Operating Precautions. The following are several of the precautions to be taken when using the 8410A and 8411A.

Maximum RF Power. Do not apply more than 50 milliwatts of RF power to the Model 8411A inputs. Power in excess of 50 milliwatts may damage the frequency converter units.

Maximum DC on RF Line. Steady state (DC) voltage on the inner conductor of the transmission line carrying signals to the Model 8411A must not exceed ±3 volts. Greater DC voltage prevents normal operation of the Model 8411A, and may damage the converter units.

This DC voltage limitation also applies when input signals are obtained from the Model 8740A Transmission Test Unit. With the Model 8741A and 8742A Reflection Test Units, however, the limitation does not apply because there is DC isolation between the main and secondary lines of the internal directional couplers.

Static Discharge. Static electrical charge on cables being connected to the Model 8411A inputs can damage the converter units. Before a cable is connected to the Model 8411A it should be discharged to the outer parts of the Model 8411A input connector. Another way to prevent static discharge is to first connect the input end of the cable to a discharge path such as that provided by the output termination of a signal source. There is no risk of static discharge when connections are made directly to Model 8740A, 8741A, or 8742A Test Units because internal terminations provide discharge paths.

Exercises (642):

1. State the purpose of the 8410A Network Analyzer and the 8411A Frequency Converter?

2. What is the dynamic range of the 8410A and 8411A?

3. The input power to the 8411A should be limited to less than how many milliwatts to prevent damage?

643. Describe the purpose of the 8413A Phase Gain Indicator and state the precautions to obtain maximum accuracy.

8413A Description. Signals from the Network Analyzer containing phase and amplitude information are fed to the 8413A through a rear-panel connector. These signals are detected in the phase-gain indicator and DC voltages proportional to phase and amplitude are fed to the 8413A meter and to front panel connectors for display on an X–Y recorder or oscilloscope. The meter displays either phase or amplitude, function and range being selected by the front-panel pushbuttons. The phase and amplitude voltages are available whenever the network analyzer is phase locked and are independent of meter function or range. A front panel phase offset control may be used to change the phase relationship of the input signals in 10° steps up to ±18°. This control effects both the meter and phase voltage output. Phase offset may be used to establish a convenient reference during phase calibration and to offset the phase angle for greater resolution during measurements.

Operating information. The greatest accuracy may be obtained during measurements of phase and amplitude if each instrument in the test setup is matched at input and output as close as possible to its design impedance (50 ohms). Attenuators are used between instruments to maintain a good impedance match at all times and to prevent interaction between instruments. The Model 8411A Harmonic Frequency Converter, especially, requires a good impedance match.

Measuring large phase angles. When measuring a phase angle near 180° on the 180° scale, the phase meter may give an erratic indication. With a high test-signal level, erratic operation may occur close to ±180°; however, with a low test-signal level, erratic meter indications may occur as low as ±150°. Accurate measurement of these signals requires the use of the PHASE OFFSET controls to bring the meter indication close to zero (center scale). This allows the phase detection circuits to operate in the most stable measurement mode, thus providing the most accurate phase measurements. This also allows the use of the lowest scale (6°) for high-resolution phase measurements.

The technique for measuring large phase angles is performed as follows:

a. Depress the 180° PHASE pushbutton.

b. Adjust the PHASE OFFSET controls for a near-zero meter indication.

c. Select the lower scales by depressing the 60-, 18-, and 6-degree pushbuttons in succession and resetting the PHASE OFFSET controls for a near-zero meter indication after each scale selection.

d. When an on-scale meter indication on the 6° range is obtained, add algebraically the PHASE OFFSET control setting and the phase meter indication. *Example:* 170° on PHASE OFFSET plus −3° on phase meter = +167° phase.

Exercises (643):

1. The front panel output connectors on the 8413A are used for what functions?

2. What does the meter on the 8413A display?

3. To obtain the greatest accuracy during a measurement using the 8413A, what should you do?

644. State the purpose of the TS1771AU RF Wattmeter and state facts about the test set.

Purpose and Application. The test set is a portable, dual-range radio frequency, absorption-type meter used to measure power output and loss in coaxial transmission lines and to assist in tuning and troubleshooting transmitting equipment. It may also be employed as a dummy load, a modulation monitor, or an RF resistor.

Description. The test set is a self-contained instrument consisting of two basic sections; a power dissipating unit (dummy load) and a meter unit with a protective cover. The meter unit is detachable from the dummy load and may be removed up to 25 feet on its attached cable for remote operation. The hinged protective cover is detachable for convenience and contains two accessory RF input connectors.

The dummy load consists of metal film on glass resistors tapped to provide the operating voltage for the meter unit and mounted in a special arrangement between two side plates to provide the proper electrical characteristics and maximum heat dissipation. The type N female RF connector on the rear is removable and interchangeable with the type C and BNC female accessory connectors. A spare crystal rectifier is contained in a shielded housing on the opposite end of the dummy load where the 25-feet-long cable is stored.

The meter unit contains a sensitive microammeter with the scale calibrated to read watts in two-ranges. A two position switch connects the meter into the circuit through a resistive calibrating network.

Exercises (644):

1. The TS1771AU RF Wattmeter has what type of power meter?

2. List the uses of the TS1771AU RF Wattmeter.

3. How many feet from the load may the meter of the TS1771AU RF Wattmeter be operated?

645. State the purpose of the 1852A High-Power Directional Coupler Set, and the accessories and applications associated.

Purpose. The high-power directional coupler set is used in conjuction with the standards and accessories found in its transit case. When used with a Hewlett-Packard HP–432B–HO5 Power Meter and an HP–478A( ) Thermistor Mount (attached to the coupler's −40 dB sidearm connector), the set functions as a direct-reading, power measurement system with a range of 1 to 100 watts. By inserting a GENRAD-type 900G10 10 dB attenuator between the coupler's −40 dB sidearm connector and the thermistor mount, power levels above 100 watts may be measured. The maximum power level at frequencies above 1.0 GHz may be computed as follows:

$$PMAX = \frac{1}{F_{GHz}}$$

where PMAX is the power in kilowatts (KW) and F_{GHz} is the frequency in Gigahertz (GHz)

With the 10-dB attenuator inserted between the coupler's −40 dB sidearm connector and the thermistor mount, all power levels read on the 432B–HO5 power meter must be multiplied by a factor of ten to obtain the correct power level being measured by the system.

The following items are contained in the directional coupler set:

a. LC (Lumped Constant) Directional Coupler Premier Microwave, Model 1852–B–29.
b. ASL (Adjustable Slot Length) Directional Coupler Premier Microwave, Model 1852–B–20.
c. Termination, General Radio Type 900W50.
d. Adapter, General Radio Type 900QNJ.
e. Adapter, General Radio Type 900QNP.
f. Attenuator, General Radio Type 900–G10.
g. Thermistor Mount, HP 478A.
h. Thermistor Mount, HP 478A–H72.
i. High Power Load, Bird Model 8251.
j. Power Meter, HP 432B–HO5.

Specifications and Ratings. Table 3-1 lists the specifications and power ratings for the Model 1852–B–29 LC (Lumped Constant), and the Model 1852–B–20 ASL (Adjustable Slot Length) Coupler is listed in Table 3-2.

Operating Precautions. The operating precautions include the use of directional coupler set, HP 432B–H05 power meter and 900–G10 pad. We will begin the discussion with the directional coupler set.

TABLE 3–1

SPECIFICATIONS AND POWER RATINGS, MODEL 1852-B-29LC

Model 1852-B-29 LC (Lumped Constant Coupler)

Freq (MHz)	Coupling	Minimum Directivity (db)	Max Vswr (All Ports)	Max Power (Watts)	Min Power (Watts)
10-29.9	40 $^{+1.3}_{-0.2}$	35	1.04	300	1
30-225	40 ± 0.3	35	1.04	300	1
226-300	40 ± 0.4	35	1.04	300	1
301-400	40 $^{+0.2}_{-1.5}$	30	1.04	300	1

TABLE 3–2

SPECIFICATIONS AND POWER RATINGS, MODEL 1852-B-20ASL

Model 1852-B-20ASL (Adjustable Slot Length Coupler)

Freq (MHz)	Coupling	Minimum Directivity (db)	Max Vswr (All Ports)	Max. Power (Watts)	Min Power (Watts)
300-2000	40 ± 0.3	34	1.04	----	1
2001-3000	40 ± 0.3	28	1.04	----	1
300	40 ± 0.3	34	1.04	1000	1
400	40 ± 0.3	34	1.04	1000	1
500	40 ± 0.3	34	1.04	1000	1
1000	40 ± 0.3	34	1.04	1000	1
1300	40 ± 0.3	34	1.04	850	1
3000	40 ± 0.3	28	1.04	577	1

a. Directional coupler set:

(1) When measuring power with the directional coupler set, always connect the coupler being used so that power flows into the coupler connector marked INPUT and out of the connector marked OUTPUT.

(2) Make certain that connectors which are to be attached to like connectors of coupler set items are undamaged. All connectors are to be tightened securely by hand. A loose connector will cause significant measurement error.

(3) Do not remove connectors from the coupler body.

b. HP 432B–HO5 power meter:

(1) Assure that the 40-dB level switch is in the "40 dB" position when using the power meter with the couplers.

(2) Do not use the 432B–HO5/478A ( ) thermistor mount without the 40-dB directional coupler (LC or ASL) when measuring power above 10 milliwatts.

(3) Ensure that the mount resistance level is in the correct position for the mount being used. (200 ω position for the 478A ( ) thermistor mounts supplied.)

(4) Set range switch to 10 W and lower range to increase resolution of measurement as necessary.

c. 900–G10 pad:

Do not disassemble the 900–G10 precision 10-dB attenuator since toxic dust can result if the resistor is crushed.

Application Information. These are some of the applications for the couplers.

LC coupler. The LC directional coupler may be used in conjunction with a thermistor mount (Hewlett–Packard 478A-H72) for measuring RF/microwave power up to 100 watts. The maximum power limit of the coupler mount may be extended to 300 watts by inserting a precision 10 dB attenuator (GENRAD-type 900–G10) between the coupler secondary port connector (labeled "−40 dB") and the thermistor mount. The coupler is to be inserted into the transmission line where power flow is to be measured with the coupler INPUT toward the source and the OUTPUT toward the load. Within the specified frequency range, the coupled (−40 dB) connector will have power which is 40 dB (nominal) below the power in the coupler main primary line. Attaching a power meter (HP–432B–HO5) and thermistor mount (HP–478A–H72) to the coupler "−40 dB" connector allows one to accurately monitor the power flowing in the transmission line.

ASL coupler. The ASL coupler is used in conjunction with a thermistor mount to measure RF/microwave power over a frequency range of 300 MHz to 3 GHz. The coupler is inserted into the line where power is to be measured with the INPUT toward the power source and the OUTPUT toward the load. A thermistor mount (HP–478A) is attached to the coupler port labeled "−40 dB." Within the specified frequency range (300 MHz to 3 GHz) the power applied to the mount will be 40 dB (nominal) below the power flowing in the line. The maximum power that may be applied to the coupler primary line with the mount attached to the −40-dB connector is 100 watts. At this power level the power applied to the mount is 10 milliwatts (mw), the maximum level which it can safely measure without damage. By inserting a precision 10-dB attenuator (GENRAD-type 900-G10) between the coupler −40-dB port and the thermistor mount the power applied to the coupler primary line can be increased to the values listed in the TO. If the power applied to the coupler primary line is greater than 100 watts, attach a 10 dB attenuator (GENRAD-type 900–G10) to the coupler −40-dB port, attach a thermistor mount (HP–478A) and power meter (432B–HO5) to the 10-dB attenuator to monitor power in the main line. The power will be 50 dB (nominal) below the power in the primary line.

NOTE: When adjusting the ASL coupler to the frequency being measured, approach the frequency marking by turning the knob in a counter-clockwise direction. This will eliminate any backlash.

Precautions for using the 432B–HO5. The following precautions should be taken when using the 432B–HO5:

a. Power levels up to 100 watts. For power levels up to 100 watts, set the 432B–HO5 power meter cal factor/vernier dials to a value within the range of 84 to 116 as shown on the calibration certificate. At frequencies where the cal factor/vernier dials to 100 and multiply the indicated power reading by 100 and divide this product by the cal factor dial setting as shown on the calibration certificate to obtain the true power.

b. Power levels above 100 watts. For power level above 100 watts the GENRAD 900–G10 10-dB attenuator must be inserted between the coupler's −40 dB sidearm connector and the thermistor mount. Set the 432B–HO5 power meter cal factor/vernier dials to a value within the range of 84 to 116 as shown on the calibration certificate (for the bolometer/attenuator/coupler unit). Multiply the indicated power meter reading by 10 to obtain the true power. At frequencies where the cal factor dial settings are outside of this range (84 to 116), set the cal factor/vernier dials to 100, multiply the indicated power meter reading by 1000, and divide this product by the cal factor dial setting shown on the calibration certificate (for the bolometer/attenuator/coupler unit) to obtain true power.

All connectors should be cleaned regularly with isopropyl alcohol or freon cleaning fluid. Should a problem arise, functional checks may be performed. However, all maintenance will be accomplished by AGMC as there are no user serviceable parts.

All items contained in the transit case (including adapters) shall be returned to AGMC for calibration.

Exercises (645):

1. Which power meter and thermistor mount are normally used with the 1852A high power directional coupler set?

2. What is the maximum power that may be measured using only the HP-432B power meter and an HP–478A( ) thermistor mount?

3. What is the attenuator that is part of the 1852A accessory kit?

4. For power levels above 100 watts, what must be accomplished to the 1852A to ensure no damage to equipment?

CHAPTER 4

Attenuators and Attenuation Measurement

IN THIS CHAPTER, we discuss some of the test equipment and methods you will use when making attenuation measurements. We also review some attenuator principles you will use in microwave test setups for making attenuation measurements and for calibration of attenuation devices. As we discuss various techniques and uses of attenuation measuring equipment, bear in mind that the results you obtain depend upon the accuracy of the standard, the physical condition of the components used in the measurement, your ability to make the measurement, and the environmental condition.

4-1. Attenuators

Attenuators are important to the operation of the microwave equipment in the PME laboratory. Attenuators are used to reduce power levels by accurate amounts for precise measurements at microwave frequencies. The attenuator used at microwave frequencies is designed very carefully, so that it presents the same impedance at all frequencies within its frequency band and attenuates the same amount for each frequency. The measurement of attenuation will be discussed in detail in a later lesson. The purpose of this lesson is to analyze the basic types of attenuators.

646. Differentiate between fixed and variable coaxial attenuators both as to their design and their uses.

Coaxial Attenuators. Coaxial attenuators are so designed that they will bilaterally match, over a broad frequency range, the characteristic impedance of the line in which they are inserted. Their attenuation response remains flat within a narrow tolerance range.

Fixed coaxial attenuators. The various configurations used in fixed coaxial attenuators are described as the series-type and the T-type. The maximum frequency design limit is approximately 10 kMHz.

The series-type fixed coaxial attenuators consists of either a single, uniform section of metalized glass for small attenuations or a series of three uniform sections, one at either end for matching, and a main attenuating section in the center, to achieve large attenuations. The two types are illustrated in figure 4-1. As shown, the ends of the metalized glass tubing are soldered to bullets, so that each unit can be inserted as the center conductor of a coaxial casing.

The electrical design of a T-type, or disk-type, coaxial attenuator (fig. 4-2) is similar to the design of low-frequency T-sections. This type of attenuator is most useful up to approximately 4000 MHz. Since, at the higher frequencies, the size of the resistive elements becomes comparable to the wavelength, a point is reached at which they can no longer be considered as lumped components. The T-type attenuator is most suitable over the frequency band of 1000 to 4000 MHz for attenuations greater than 10 dB, and the SWR is usually around 1.3.

The shunt element may consist of either mica or glass which is coated with a metallic film. This provides a large surface area for obtaining the necessary resistance. Below 10 dB, the resistance value must be large. To obtain this resistance value, the corresponding film may have to be so thin that fabrication would become extremely difficult.

Variable coaxial attenuators. Variable dissipative coaxial attenuators are devices which employ a means for shorting out a portion of a metalized glass element. The resulting attenuation is proportional to the film which remains exposed to the microwave power. The "lossy" element may be placed either in series or in shunt within a coaxial casing. (The term "lossy" means an insulating material which dissipates more than the usual energy.)

These arrangements of the variable coaxial attenuator are used in most applications. The first type employs a metal rod which is inserted into the metalized-glass tubing from the far end of the attenuator. The attenuation is dependent upon the position of the rod. The coupling between the rod and film is through the glass. The second type uses a close-fitting metal tube which slides over the metalized-glass element. In the third type, a metalized-glass plate is inserted, in shunt, through a slot in the outer conductor of a coaxial line. A variation of this is to fix the lossy plate between the inner and outer conductors and to insert a movable short circuit from the outer conductor.

Exercises (646):

1. What is the approximate maximum frequency design limit of coaxial attenuators?

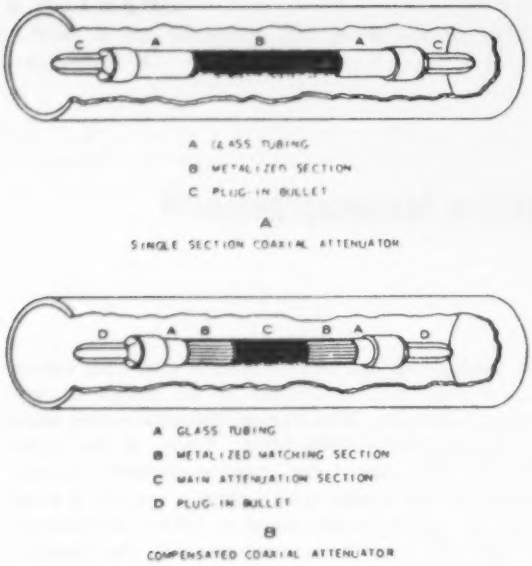


Figure 4-1. Series-type coaxial attenuators.

2. What is the upper limit of the T-type coaxial attenuator?

3. What main factor limits the lowest value of attenuation that can be attained in fixed coaxial attenuators?

4. What means is employed to produce variable dissipative coaxial attenuators?

647. Identify the major types of waveguide attenuators with their construction operating characteristics.

Waveguide Attenuators. Both fixed and variable attenuators for rectangular waveguides usually employ resistive plates inserted parallel to the E-field. In precision types of attenuators, the resistive element is a metalized-glass plate which may be inserted either from one of the narrow side walls or through a slot milled in the center of the upper wall. The former is referred to as the vane type, or transverse insertion type. The latter is known as the flap type, or guillotine type. Both types provide bilateral matching. A rotary type may also be designed by using a metalized-film element which rotates within a round guide flanked by rectangular-to-round transition.

Vane-type attenuator. The vane-type attenuator makes use of an element which has matching sections near both ends; some matching methods are shown in figure 4-3. The exact dimensions of the elements are determined experimentally; however, for a mean waveguide wavelength (λg), resistive transformer matching sections are approximately $\lambda g/4$ in length. The taper match (fig. 4-3) is approximately $\lambda g/2$ long. Of the two methods, the resistive transformer match is preferred, since it results in broadband responses and is simpler to fabricate. The design of metalized-glass plates is based on a systematic variation of plate dimensions, a plate dielectric, and the surface resistivity of the metallic film until desired attenuation and SWR characteristics are realized with minimum frequency sensitivity.

The casing design incorporates properly spaced metal struts which support the metalized-glass element (fig. 4-4). Usually, two struts are used, spaced at odd multiples of the mean waveguide wavelength apart. If the struts are not so placed, they will introduce shunting capacitances and,

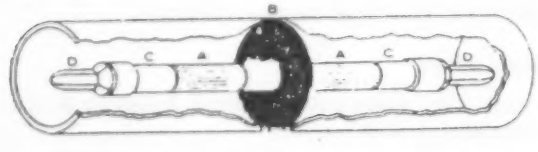


Figure 4-2. T-type coaxial attenuator.

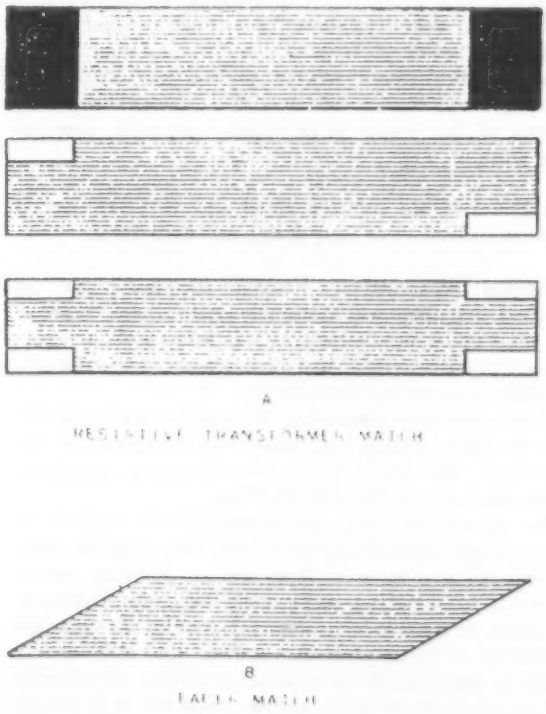


Figure 4-3. Matching methods for vane-type attenuators.

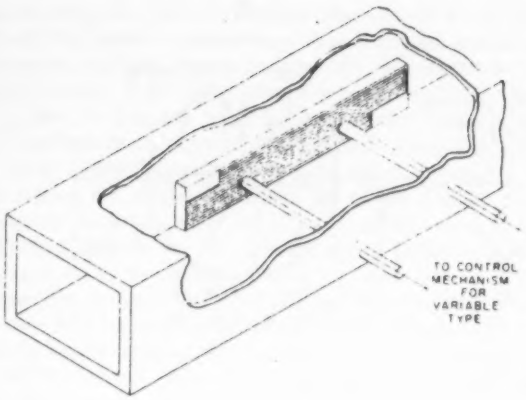


Figure 4-4. Vane-type waveguide attenuator.

therefore, error. For variable attenuators, a precision screw mechanism with a dial connected to it controls the insertion of the plate within the guide. Attenuators of this type have been designed to provide an attenuation range from 0 to 40 dB, with SWRs of less than 1.12 for signals as high as 18 kMHz.

Flap-type attenuator. The resistive element for flap-type attenuators is shaped like an arc of a circle to achieve bilateral matching. In precision types, a drive mechanism lowers the glass plate into the guide through a narrow slot. The degree of strip penetration determines the amount of attenuation. Since the attenuation of the plate increases exponentially, a nonlinear drive is used. The attenuators of this type which are used in the PME field normally cover the attenuation range of 0 to 20 dB, with SWRs of less than 1.15 in the frequency range for which they are designed.

Rotary-type attenuator. In your work, the most widely used attenuator of this type is the HP–382A. The HP–382A operates on the principle of splitting the signal into two components and absorbing one of them. This is done by using three resistive films, two fixed in the end sections and one mounted in a rotatable center section.

The films are made by evaporating resistive material onto thin mica sheets. These films are clamped between waveguide halves in order to make electrical contact between the films and the waveguide walls.

The end sections of the attenuator consist of rectangular-to-round transition, with the films fixed at right angles to the E-field. The center section is a round waveguide with choke joints at the ends to allow the center section to be rotated (fig. 4-5).

Essentially, the $TE_{0,1}$ input waveguide mode is converted to a $TE_{1,1}$ circular mode and then reconverted to the $TE_{0,1}$ mode after the E-field has been attenuated by the rotary vane. The E-field of the $TE_{0,1}$ mode is not dissipated by the first fixed vane, since the field is normal (perpendicular) to the vane. This is shown in figure 4-6,A. Referring to figure 4-6,B, in the circular guide, the E-field may be resolved into components. One component, E sin θ, lying parallel to the vane is dissipated. The other component, E cos θ, is normal to the vane and is unaffected. Upon passing to the second fixed vane (output vane), figure 4-6,C, E cos θ is resolved into a vertical component, E $\cos^2$ θ, and a horizontal component, E sin θ cos θ. Due to the horizontal position of the fixed resistive vane, the E sin θ cos θ component is absorbed, while the E $\cos^2$ θ component emerges at the output as shown in figure 4-6,D. In terms of dB, the attenuation is as follows:

$$\text{Attenuation} = 20 \log \cos^2 \theta$$

or, for easier calculations:

$$\text{Attenuation} = 40 \log \cos \theta$$

The principal sources of error in the HP–382A are internal reflections and finite attenuation in the rotary film. Reflections are minimized by tapers on the films and careful design of the transitions and choke joints. The rotary film attenuation is made as great as possible consistent with low reflections and reasonable length and is approximately 70 dB. However, it is not possible to calibrate the instrument all of the way to 90° rotation. Since a margin of about 20 dB is necessary to maintain accuracy, calibration is carried only to 50 dB.

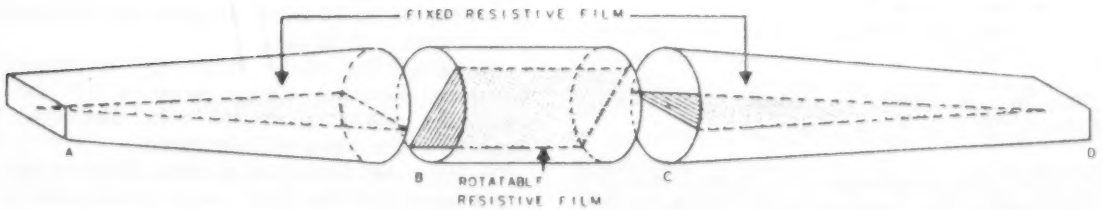


Figure 4-5. Phantom view of rotary-vane attenuator.

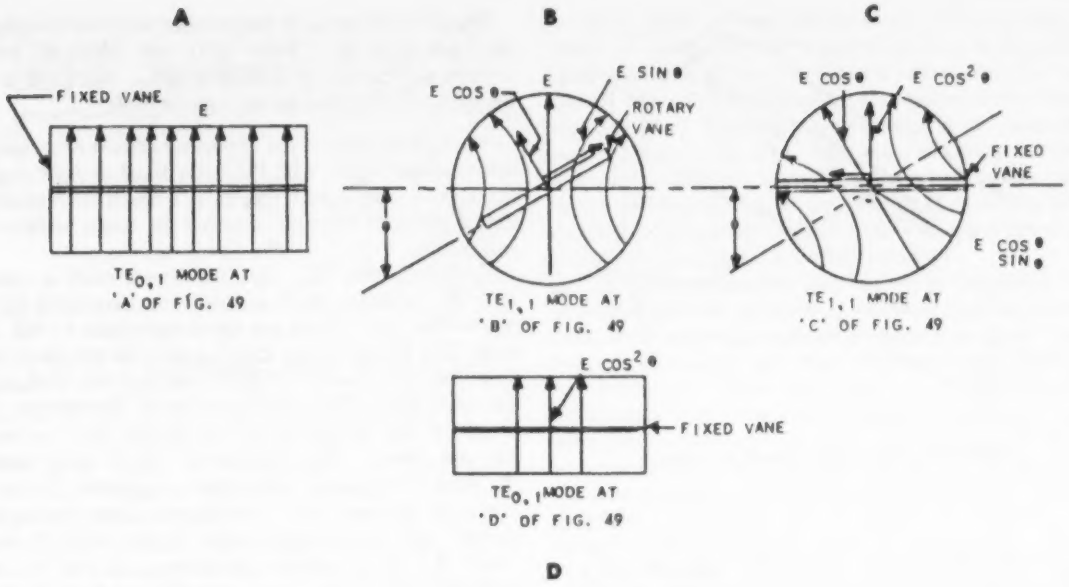


Figure 4-6. Attenuation of E vector as it traverses the rotary-vane attenuator.

Exercises (647):

1. Match the type of attenuator in column A to the appropriate construction and operating characteristics in column B. Some column B items may be used more than once.

Column A	*Column B*
____ (1) Splits signal into two components and absorbs one of them.	a. Flap-type attenuator.
____ (2) The degree of strip penetration determines attenuation.	b. Rotary-type attenuator.
____ (3) Attenuation range normally from 0 to 20 dB.	c. Vane-type attenuator.
____ (4) SWRs of less than 1.12 for microwave signals under 18 kMHz.	
____ (5) Changes the angle of the center to vary amount of attenuation.	
____ (6) Resistive element is shaped like an arc of a circle.	

648. State facts concerning operational characteristics of the Model 355C/D/E/F attenuator.

355C/D/E/F Step Attenuator. The Model 355C/D/E/F is a direct-reading step attenuator usable from dc to 1000 MHz. The Model 355C/E provides 0 to 12 dB attenuation in 1-dB steps, and the Model 355D/F provides 0 to 120 dB in 10-dB steps. Connected, the Models 355C/E and D/F provide a range of attenuation of 0 to 132 dB in 1-dB steps. SWR, error, and residual attenuation are low at all settings. Input and output connectors are female-type BNC. Input and output impedances are 50 ohms, nominal.

Specification 355E/F is a standard HP Model 355C/D in which the standard shaft with cams which normally activate the microswitches has been replaced by four solenoids to allow remote programmable operation. The solenoids operate the microswitches to proper combinations to obtain the desired degree of attenuation. The solenoids are push-type, continuous duty and each solenoid draws approximately 1/6 amp at 25 volts dc. Programming is achieved through a connector in the housing.

The 355C/D is compact, rugged, and well-shielded.

The 355C/D drive mechanism, controlled from the front panel, is a single rotary shaft which mounts four cams. The cams drive eight microswitches in pairs. The microswitches set up connections, in the proper sequence, to obtain the desired degree of attenuation, to four πtype attenuator pads.

The Model 355C/E has pads of 1, 2, 3, and 6 decibels which allow a range of 0 to 12 dB in 1-dB steps; the Model 355D/F has 10, 20, 30 and 60-dB pads which allow a range of 0 to 120 dB in 10-dB steps.

Operation. The Model 355C/D/E/F is designed to dissipate a maximum average power of 0.5 watt and accomodate pulses up to 350 volts maximum. The attenuator will be damaged if overloaded.

The input may be applied to either connector and the output taken from the other, except in the case of the 355D/F driven from a low impedance source. In this one case, the leaf switch may be closed before the microswitch

opens when the dial is switched from 50 dB to 60 dB. Should this occur, a momentary short is placed across the connector, inviting damage to either the microswitch or the signal source. If the signal source is capable of delivering more than 10 amperes, use the rear connector for the input. This pads the momentary short with 50 dB of isolation.

Up to 132-dB attenuation in 1-dB steps is available by connecting the Model 355C/E to the Model 355D/F. The connector location on the 355D/F is the mirror image of the connector location on the 355C/E, which permits the two attenuators to be mounted side by side with a short connection between them. A standard UG-491A/U male-to-male BNC adapter or an HP 803A-16E Cable Assembly may be used to connect the two units.

NOTE: The HP 803A-16E Cable Assembly, a solid (low leakage) coaxial cable, is recommended over flexible coaxial cable.

The Model 355C/D may be operated by remote control since it is switched by rotating one shaft.

Exercises (648):

1. The Model 355 is what type of attenuator?

2. State one advantage of the Models 355E/F over the Models C/D.

3. The Model 355 C/D/E/F is designed to dissipate what maximum average power?

4-2. Attenuation Measurements

In this section, we discuss several methods that you can use in making attenuation measurements. As in other measurements you will make in a span of measurement, and your skill determines which method you use for a particular measurement.

649. Define two types of transmission line losses and differentiate between them.

Transmission Line Losses. Attenuation is the ratio of power leaving a network to power entering a network (fig. 4-7) when both the input and output are perfectly matched

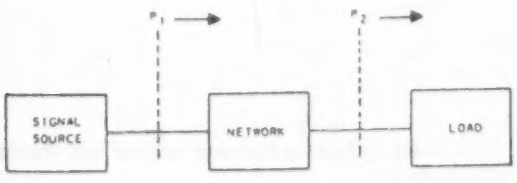


Figure 4-7. Power-ratio variables.

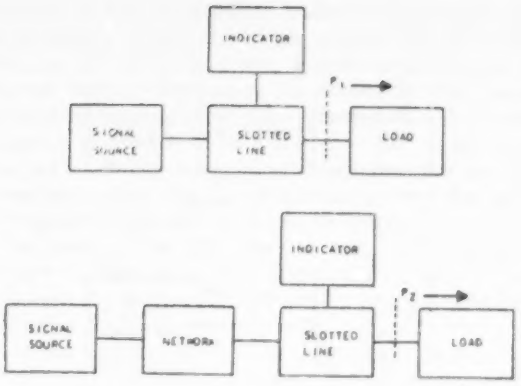


Figure 4-8. Insertion-loss variables.

to the source and the load, respectively. Hence, no mismatch occurs at either terminal of the network. The attenuation is commonly expressed in decibels by:

$$A_a = 10 \log \frac{P_1}{P_2}$$

Insertion loss. Insertion loss is defined as the ratio of power absorbed by a load before and after the network is inserted in the system (fig. 4-8). For meaningful measurements, the load and source are both tuned to match the line so that unity SWR exists. The insertion loss in decibels is expressed as:

$$A_i = 10 \log \frac{P_1}{P_2}$$

The insertion loss consists of two factors: (1) the attenuation of the network and (2) the mismatch losses occurring because the impedances at the source-network and load-network junctions are not matched.

Mismatch loss. Mismatch loss is defined as the difference between the power which would be absorbed by a network if it were perfectly matched to the source and the power which is absorbed by the network with existing network impedance (fig. 4-9). The mismatch loss in decibels is expressed as:

$$A_m = 10 \log \frac{Pi}{Pi - Pr}$$

Mismatch loss occurs whenever the impedances at a junction are not matched. If the network has an input impedance that matches the output impedance of the source, all of the incident power is absorbed by the load and no loss occurs. If the junction impedances are not matched, an amount of loss exists that depends upon the phase of the reflection coefficients. If the reflections add in-phase, a maximum SWR results at the junction, producing a maximum loss. If they subtract, a minimum SWR occurs, producing a minimum loss.

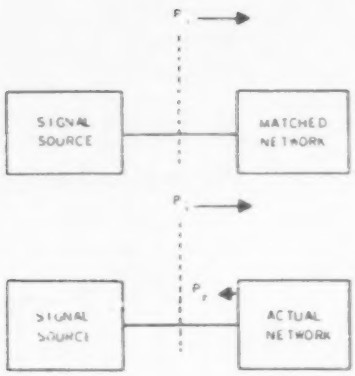


Figure 4-9. Mismatch-loss variables.

Sometimes it is desirable to eliminate the effects of a high load or source SWR for matching purposes. A pad in series with the load or source provides SWR reduction. Consider the example given in figure 4-10.

The incident power into the pad is P_1. An attenuated amount of this power is received at the load, and part is reflected. The reflected power is also attenuated when it is passing through the pad. The resulting SWR, looking into the pad and load, is much less than that of the load alone. If the pad has a negligible SWR, the effective SWR of the combination can be calculated from the formula:

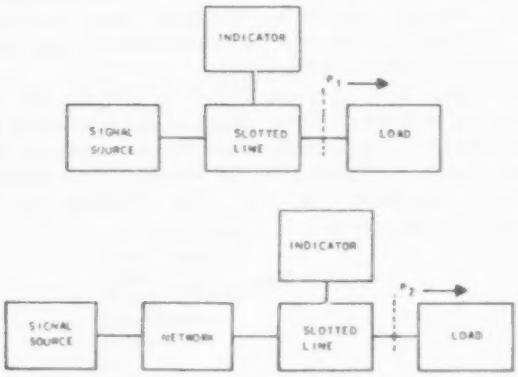


Figure 4-8. Insertion-loss variables.

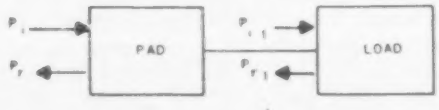


Figure 4-10. SWR reduction variables.

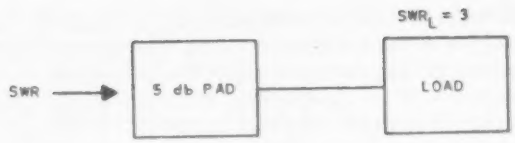


Figure 4-11. SWR reduction calculations.

$$SWR = \frac{R(SWR_L + 1) + (SWRL_L - 1)}{R(SWR_L + 1) - (SWR_L - 1)}$$

SWR_L = SWR of load or source

R = ratio of power input to power out of the attenuator

$= \text{antilog} \frac{a}{10}$

If a 5-dB pad is placed in series with a load having an SWR of 3 (fig. 4-11), the resulting SWR of the combination is (for this example,

$$R = \text{antilog of } \frac{5}{10} = 3.16:$$

$$SWR = \frac{3.16(3 + 1) + (3 - 1)}{3.16(3 + 1) - (3 - 1)}$$

$$= \frac{12.64 + 2}{12.64 - 2}$$

$$= 1.39$$

Absolute attenuation and relative attenuation are terms frequently referred to in attenuation measurements. Absolute attenuation is the total amount of attenuation presented by a network and is illustrated by such devices as fixed pads or lengths of cable. Relative attenuation is the change of attenuation found in such devices as variable attenuators. For example, a variable attenuator might be calibrated from 0 to 50 dB, which means that the amount of relative attenuation can be varied from 0 to 50 dB. The absolute attenuation of the attenuator also includes the insertion loss. Therefore, if 20 dB is indicated on the dial and the insertion loss is 1 dB, the absolute attenuation is 21 dB.

Exercises (649):

1. The ratio of power absorbed by the load before and after the network is inserted in the system is defined as _____ _____ .

2. Define the difference between insertion loss and mismatch loss.

3. What is the difference between relative and absolute attenuation?

4-3. Attenuation Measuring Methods

Several methods of measuring the attenuation of a network are used. Since the two methods you will be mainly concerned with in the PME field are the insertion method and the substitution method, only these methods will be discussed here.

Of the two methods described, the substiution method is commonly used for high accuracy measurements of both fixed and variable attenuators. In the substitution method, the attenuator under test is compared with a precision attenuator. This method is used for high accuracy measurements more often than the insertion method for high accuracy measurements, because the output amplifier and the indicator are always operated at the same level. Therefore, any nonlinearity in the amplifier or indicator system is not reflected in the accuracy of the measurements.

We shall describe two actual system setups for attenuation measurement. You will need to know both systems to increase your proficiency in the microwave area of PME. These systems are the linear and the square-law detecting systems. One system uses a linear detector, standard attenuator, receiver, and indicator; the other system uses a square-law detector, standard audio attenuator, amplifier, and indicator. The total amount of attenuation that can be measured is the principal difference between the two systems. Both systems have comparable accuracies. The linear detecting system is capable of measuring approximately twice as much attenuation as the square-law detecting system; however, the linear detecting system requires more equipment.

650. State the purpose of the first tuner in the single-channel system and specify its measurement principle.

Single-Channel Attenuation Measurement Method. Refer to figure 4-12 during the following discussion. In this method, attenuation is measured by substituting the attenuation of the unknown attenuator for the attenuation of the precision attenuator. The barretter is supplied by a constant current source. Since the change in resistance level is proportional to the input RF level, the audio voltage developed by the barretter element is proportional to the input power. This voltage is attenuated, amplified, and displayed in the HP–415B. The bolometer current is selected, so that the barretter is operating over the most linear portion of the square-law region. The RF power level, the HP–415B attenuator, and the amplifier gain are adjusted for an indication on the HP–415B. The source-modulating frequency is also adjusted for the center frequency of the HP–415B (1000 Hz). The source power must not be set high enough to drive the barretter out of its square-law region. The amount of source power that can be used depends upon each individual barretter.

The probe of the first tuner is completely withdrawn during the initial setup. The second tuner is used to match the barretter to the line. To perform this matching, the tuner is adjusted for maximum indication on the HP–415B, and this indication is recorded. Next, the attenuator under test is inserted between the two tuners. The attenuation of the HP–415B audio attenuator is decreased to get an upscale reading on the HP–415B indicator. The first tuner is adjusted next to match the unknown attenuator to the system. A reading is again taken from the HP–415B. The attenuation of the instrument under test is then computed as the difference between the initial and final HP–415B readings. (NOTE: For insertion loss measurements, using the procedure just given, both tuners are adjusted so that unity SWR exists when looking into the generator and into the load.)

Since the audio frequency voltage developed across the barretter is proportional to the RF input power, a 10-dB reduction in the RF level causes a 20-dB reduction in the audio frequency level. So if, for example, a 10-dB pad is measured, 20 dB of audio attenuation must be removed to obtain the same indicator level. Units specifically designed for attenuation measurements with square-law detectors have an audio attenuator calibrated, so that a 10-dB reduction in the RF level into the barretter is shown as a 10-dB change on the indicator. The HP–415B is calibrated in this fashion.

This system of measuring attenuation can be used over a wide frequency range. It has been used successfully between 10 MHz and 40 kMHz. In fact, it may be used wherever suitable barretters and barretter mounts are available.

The range of attenuation that can be measured in one step depends upon the linearity of the barretter and upon the noise level. The maximum range of most barretter and amplifier combinations is approximately 30 dB. At this

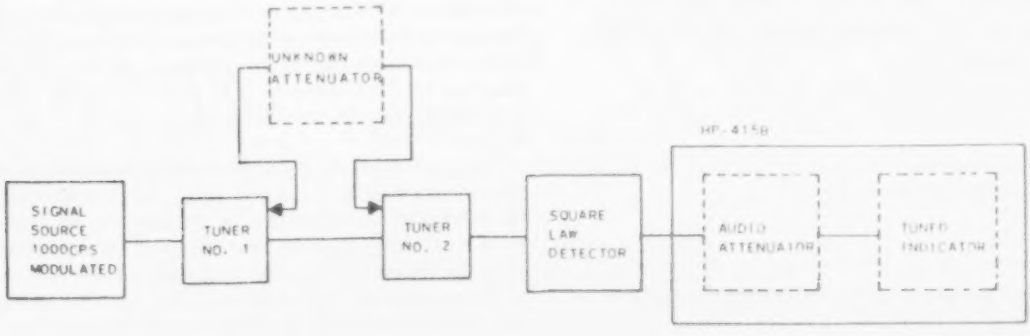


Figure 4-12. Attenuation measuring system using square-law detection.

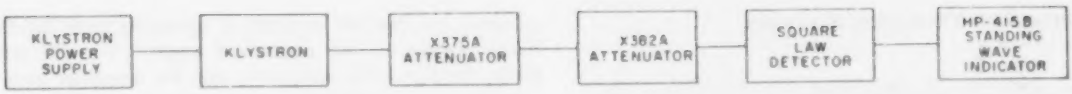


Figure 4-13. Substitution method of attenuation measurement.

range of operation, the error is generally no more than 0.05 dB. An attenuation of 20 dB can be measured easily with this system. Measurements above 20 dB, however, must employ certain precautions so that the square-law region of the barretter is not exceeded. The total amount of attenuation that can be measured is determined by the available source power. The procedure for measuring the attenuation of variable attenuators requires measuring the attenuation in steps of 20 dB or less.

To use the substitution method of attenuation measurement, the equipment is set up as shown in figure 4-13. The measurement is accomplished as follows, using the X382A as the standard attenuator:

a. Turn on the klystron power supply and adjust the klystron for the desired frequency.

b. Set the X375A dial to 10 dB. Set the X382A to provide a zero indication on the HP–415B (30-dB range). Record the X382A reading.

c. Set the X375A to 15 dB. Reset the HP–415B to zero by decreasing the attenuation of the X382A. Record the X382A reading.

d. The actual change in attenuation of the X375A is the difference between the two readings of the X382A.

NOTE: Since both readings are taken with the same power level at the detector and HP–415B, the only source of error is the X382A attenuator; and it is not necessary to be within the square-law detection range.

The accuracy of measurement in a single-channel system depends upon several factors. These include the (1) square-law region of the barretters (fig. 4-14), (2) frequency and amplitude stability of the source modulation, (3) proper matching between the system and the attenuator, and (4) the accuracy of the precision audio attenuator. The amplifier and the indicator usually introduce negligible error, since they are always operated at nearly the same power level.

Exercises (650):

1. What is the purpose of the first tuner in the single-channel system?

2. What measurement principle is used in the single-channel method of measurement?

3. What determines the range of attenuation that can be measured?

4. In making an attenuation measurement using the single-channel setup and square-law detection, you find that the RF input to the barretter is reduced by 5 dB and that the audio attenuation is reduced by 10 dB when an attenuator is inserted in the line. What change will be shown on the indicator?

651. Compare the dual-channel and single-channel attenuation measurement methods; state what inaccuracy the dual-channel eliminates; and specify how reduction in RF level is measured.

Before proceeding with the dual-channel method of attenuation measurement using the BA–5, let us review the instrument itself as shown in figure 4-15.

The BA–5 consists of a precision audio attenuator, a low-noise amplifier selective to 1000 Hz, and an indicator provided with SWR and dB scales. A cathode follower output allows the use of an external meter or recorder. This output is also used in the dual-channel setup.

The Dual-Channel Attenuation Measurement Method. The dual-channel method for attenuation or insertion-loss measurements also employs a square-law detector. This system eliminates inaccuracy in measurement caused by source instability. Therefore, it is used primarily where source instability limits the accuracy of the measurement. Figure 4-16 shows a setup for insertion-loss measurements.

In this method, an RF source of the desired frequency is square-wave modulated at a 1000-Hz frequency. The RF signal is divided into two channels: the measurement channel and the reference channel. The two RF signals derived from the same generator are detected in two bolometers, which are operated in their square-law regions; that is, the voltage at the modulation frequency developed across the bolometer is proportional to the RF power absorbed by the bolometer. The 1000-Hz signals from the bolometers are then amplified and applied to the null detector.

To measure insertion loss, the precision attenuator in the BA–5 is first set to include slightly more attenuation than the expected insertion loss of the unit to be tested or calibrated. The gain in the reference channel and the phasing adjustments on the null detector are adjusted to produce a null reading on the null detector. The unit under test is then inserted in the measurement channel, as shown in figure 4-16. Audio attenuation is then removed in the BA–5 until a null indication is again obtained. The amount

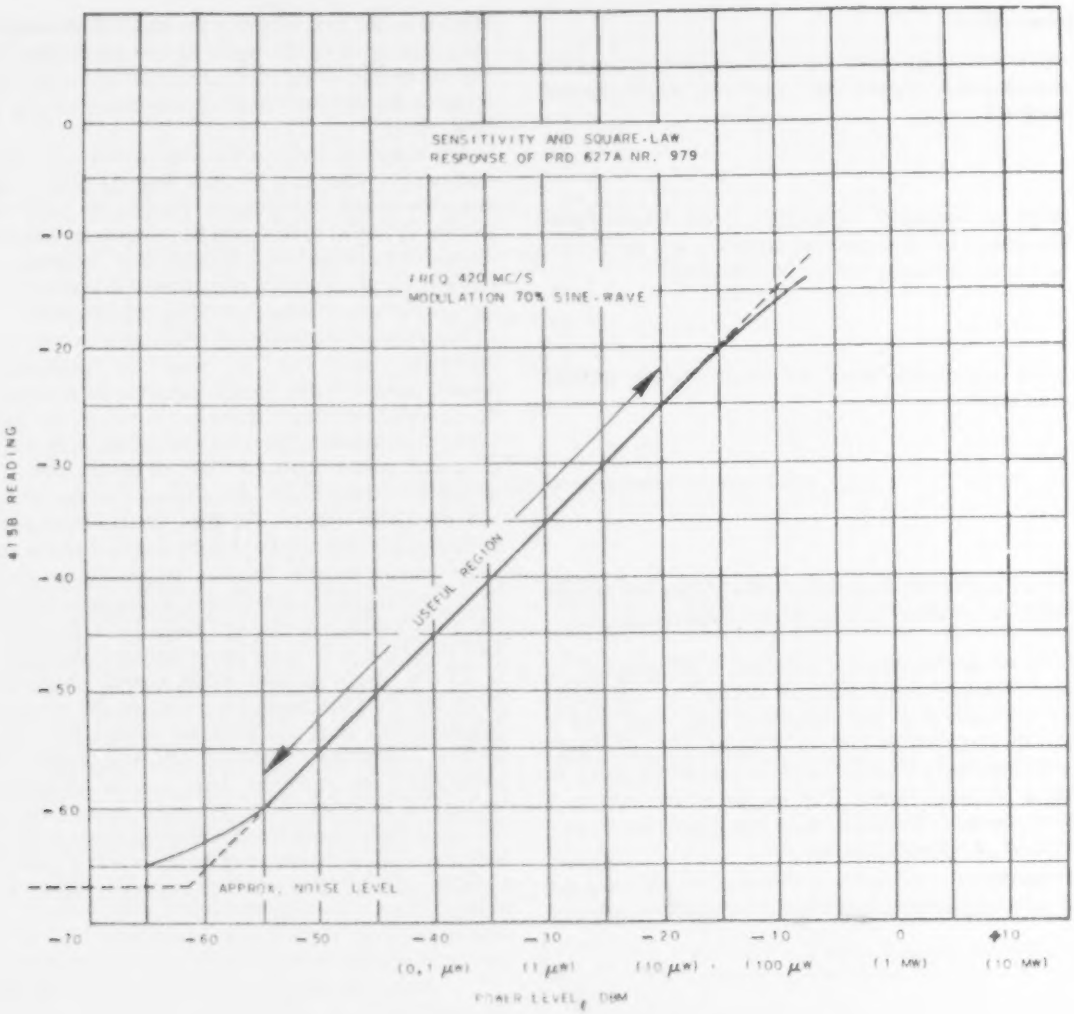


Figure 4-14. Sensitivity and square-law response PRD 627A No. 979.

of audio attenuation removed is a measure of the insertion loss of the unit under test. The output of the measurement channel is not necessarily returned to the same level as before insertion of the unit under test, but rather to a value to produce a null reading on the null detector. If the RF source has drifted since the first null adjustment, the reference channel has changed by a proportionate amount; and the measurement channel output required to produce a null is automatically compensated.

Figure 4-15. BA-5 block diagram.

Exercises (651):

1. What advantage does the dual-channel attenuation measurement method have over the single-channel method?

2. After an attenuator is inserted in the measurement channel of the dual-channel system, using the BA–5, how is the reduction in RF level measured?

3. What inaccuracy does the dual-channel method eliminate?

652. Using the linear detection method, state the factors that limit the accuracy of attenuation measurements.

The Linear Detection Method. Attenuation is measured, using a linear detection system, by comparing the RF attenuation of the attenuator under test with a standard IF attenuator. As shown in figure 4-17, the signal source is heterodyned with a local oscillator in a mixer to provide a 30-MHz output. The output is admitted to a precision standard attenuator, then amplified, and finally displayed on an indicating device.

Measurement. Attenuation is measured by adjusting the source power for a meter indication, inserting the attenuator under test, and then adjusting the standard attenuator for the same indication on the meter as was previously obtained. The attenuation of the attenuator under test is the difference between the original standard attenuator setting and the final setting.

The range of frequencies over which this attenuation measuring system can be used depends chiefly upon the available mixers and sources. That is, the local oscillator and the RF signal source must be so stable in frequency that the two of them can hold a 30-MHz beat. Currently, mixers and sources are available that allow this system to be used for measurements between 40 MHz and 18 kMHz.

The amount of attenuation measurable in one step, with negligible error due to noise or nonlinearity, is approximately 50 dB. Greater amounts of attenuation can be measured by using more steps; however, the amount of attenuation which can be measured is limited by the amount of source power available. For example, with a source having a 10-dBm output and a mixer that can be operated with negligible error to −80 dBm, 90 dB of attenuation can be measured to the accuracy of the standard attenuator.

To achieve greatest accuracy and maximum range, the characteristics of the system must be determined before any attenuation measurements are made. First, the level of the local oscillator must be set for the lowest mixer noise figure or for the operating point where a small change in local oscillator level has negligible effect on the mixer output. Adjusting the local oscillator for lowest noise figure is usually impractical, because this can result in poor sensitivity. The optimum level can be determined by varying the local oscillator input to the mixer while holding the signal input constant and noting the mixer output on the indicator. The oscillator must be so set that a small change in local oscillator level produces negligible change in mixer output.

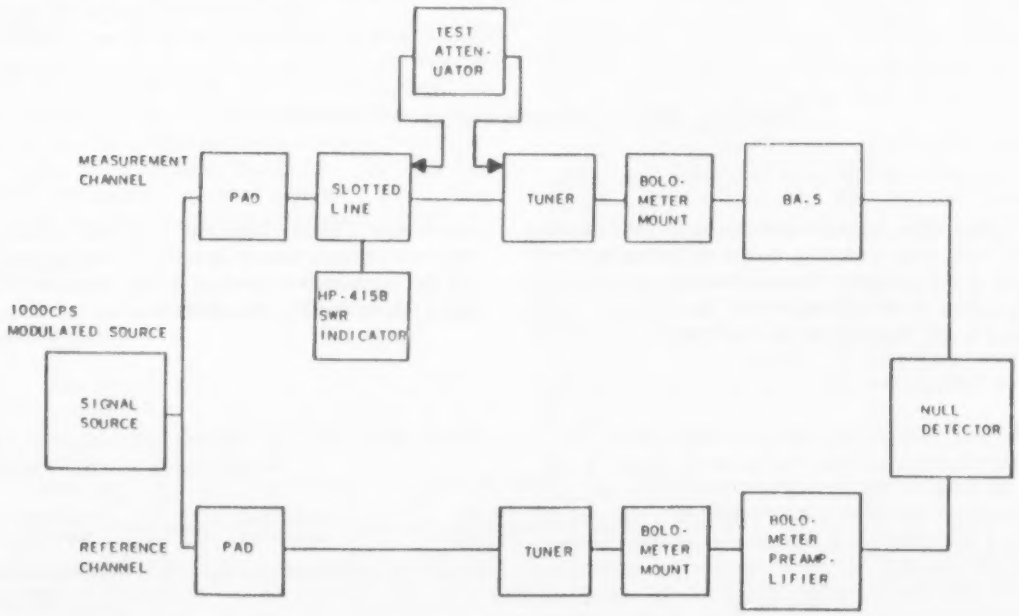


Figure 4-16. Dual-channel setup for insertion-loss measurements.

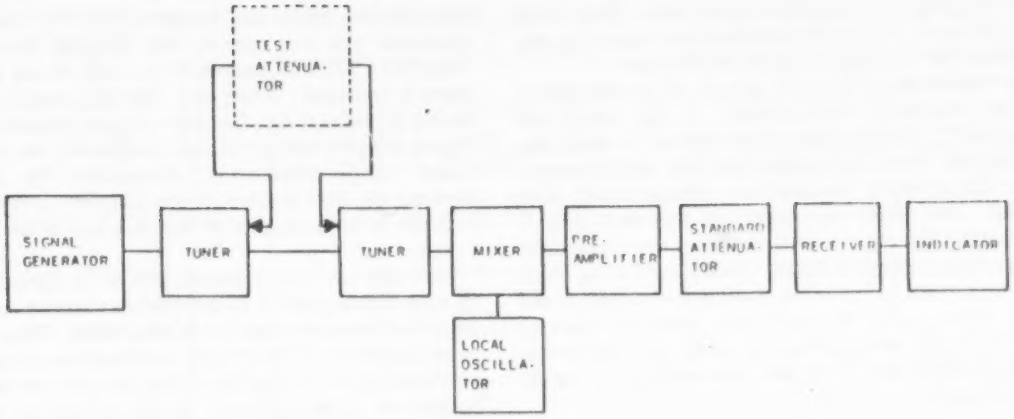


Figure 4-17. Linear detection system for attenuation measurements.

The dynamic range of the system must also be determined. If the preamplifier is operated at minimum gain, the linearity of the mixer determines the upper power limit. Mixers are limited (1) by noise at low levels and (2) by nonlinearity at high levels. The dynamic range can be determined by repeatedly measuring a fixed attenuator at various input power levels to the mixer. A decrease in the measured attenuation will be noted both when the mixer starts to operate in the noise and when it is overdriven. A knowledge of the dynamic range permits optimum operation of the system.

The accuracy of measurement with a linear detection system depends upon several variables: (1) nonlinearity of the mixer, (2) signal level versus noise level, (3) amplitude and frequency instability of the sources, (4) accuracy of the standard attenuator, and (5) mismatch in the system.

At higher power input, nonlinearity occurs in either the mixer or the preamplifier. The effect of nonlinearity can be noted by measuring a fixed attenuator, as we have previously discussed.

The ideal lower limit of signal level is set by thermal noise, while the actual limit is above the ideal because of conversion loss in the mixer and excess noise in both the mixer and the IF amplifier. The amount by which the actual limit exceeds the thermal noise limit is given by the noise figure (NF), which is defined by the following formula:

$$NF = L_C \ (N_R + N_{IF} - 1)$$

where L_C is the conversion loss of the mixer (ratio of RF power input to IF power output), N_R is the noise ratio of the mixer (ratio of its noise output to that of a resistor at the same temperature), and N_{IF} is the noise figure of the IF amplifier. Noise figure is a power ratio and is usually expressed in dB. Typical values for a 1N21C crystal mixer are as follows:

L_C — 2.8 to 3.5
N_R — 1.15 to 1.55

With an IF noise figure of 1.5 to 2.5 dB, the difference between the thermal noise limit and the actual noise limit ranges from 4.5 to 9.0 dB. Now that we have found the difference between the thermal noise limit and the actual noise limit, we must still find the thermal noise limit to calculate the overall noise level. To do this, we use for an example a receiver having a bandwidth of 2 MHz. The corresponding noise level can be found from the formula:

$$\text{Thermal noise} = KTB$$

where

B = receiver bandwidth between half-power points
*K = Boltzmann's constant
= 1.38×10^{-23} joule (watt-second per degree Kelvin)
*T = absolute temperature in degrees Kelvin

*When noise calculations are being made, the reference standard temperature, T = 290° Kelvin (62.6° F), is often used; this gives KT the convenient value of 4×10^{-21}

Therefore, substituting the numerical values in the formula, KTB, we have:

$$(4 \times 10^{-21})\ (2 \times 10^{6}) = 8 \times 10^{-15} \text{ watts}$$

$$= -111 \text{ dBm}$$

The thermal noise level then is -111 dBm. However, when no discrimination against image frequencies exists, the effective bandwidth-to-noise ratio is doubled, making the thermal noise level −108 dBm. Thus, the noise output of the overall system corresponds to a noise level of about −100 dBm at the mixer. While it is possible to operate down to noise level by making suitable corrections for its effect, most accurate results are obtained by keeping the signal level well above noise. A level of about −80 dBm is normally attainable without appreciable error due to noise.

The standard attenuator used with this system is a waveguide-beyond-cutoff type. The attenuation of this type

depends only upon its physical dimensions. Since these dimensions can be accurately machined and measured, the calibration of the attenuator is accurately known.

Recall that in this section, we described the two system setups for attenuation measurement, (1) the square-law detecting and (2) the linear detecting systems. In discussing the square-law detecting system, both the single-channel and the dual-channel measurement arrangements were mentioned. The main advantage of the dual-channel arrangement is that source instability does not appreciably affect the measurement accuracy. You should have noted that one precaution for avoiding errors in measurement was stressed: When using the square-law detection system, extreme care must be exercised to ensure that the source power is not high enough to drive the barretter out of its square-law region.

Exercises (652):

1. What determines the frequency range of the measuring system?

2. What variables determine the accuracy of a linear detection system?

3. What is the noise level when a linear detection system is used with a receiver having a 4-MHz bandwidth?

653. State the purpose of the VM–3 when it is used as an IF substitution system; state what output provides it full utilization; and identify its attenuator and readout.

IF Substitution Method. For our coverage of the IF substitution method of attenuation measurements, we discuss the VM–3 and the associated circuits necessary for making attenuation measurements. This system is commonly referred to as the parallel IF substitution system.

Briefly, let us look at how a measurement by this method is made. An external signal generator and a local oscillator are connected to a 30-MHz linear mixer, and the microwave signal is converted to an IF signal of 30 MHz. This external 30-MHz IF signal is compared with a 30-MHz internal reference signal, which may be adjusted in level by using a calibrated precision waveguide below cutoff attenuator. These two 30-MHz signals are alternately received in an IF amplifier. The external signal is either 100 percent square-wave modulated in counterphase with the internal 30-MHz signal; or, if the external signal is a CW signal, it is alternately chopped on and off by a 1000-Hz electronic switch inside the VM–3. These two alternate signals are fed to the IF amplifier, which is used only to detect a difference in level between two 30-MHz signals.

For this reason, the gain of the IF amplifier is not critical. An AGC loop is provided to the IF amplifier, which automatically keeps the detector sensitivity constant. In operation, the two signals are adjusted to the same amplitude, which is indicated by a null on the amplitude balance indicator. After this, the unknown microwave device is inserted into the measurement channel, and the system is again brought to null by adjusting the waveguide below cutoff substitution attenuator. The difference between the two settings of the standard attenuator is a measure of the attenuator or insertion loss of the unknown device.

Now that you have a general idea of the operation of the IF substitution method of attenuation measurement, let us study the necessary elements in this system. There are three basic elements—a comparator, a heterodyne mixer, and an oscillator mixer. In our discussion, we describe the HO–1 heterodyne mixer oscillator, the HO–A heterodyne mixer, and the VM–3 attenuator and signal calibrator. All three units must be married for this system to operate as an IF substitution attenuation measurement system.

HO–1 heterodyne mixer oscillator. This system provides a complete local oscillator mixer system for the heterodyne conversion to 30 MHz, or signals in the frequency range to 10 MHz. The oscillator eliminates the need for six or seven local oscillators with associated power supplies and mixers.

The HO–1 contains two microwave oscillators, together with their associated power supplies. Both oscillators are required for dual conversion in the signal frequency band from 10 MHz to 1990 MHz. The first oscillator is tunable from 2020 MHz to 4200 MHz, while the second oscillator operates at a fixed frequency of 2060 MHz. From 1990 to 4200 MHz, fundamental mixing is employed; and from 4150 to 12,400 MHz, second and third harmonic mixing is used. The direct-reading dial on the unit is calibrated for signal frequency operation in the fundamental, harmonic, and dual conversion modes. Only one knob for control is needed for tuning the signal frequency. All the voltages are automatically tracked.

HO–A heterodyne mixer. The mixer module is a part of the HO–1 system and is connected to the HO–1 oscillator module by means of cables. This module contains the necessary directional couplers, filters, and diode mixers to convert an external signal to a 30-MHz IF over the full range from 10 MHz to 12.4 GHz. The external signal sources that you use in the attenuation setup must provide at least −10 dBm output available at the HO–A input to use the full dynamic range of the receiver.

Now that we've discussed the circuits which convert the external signal to a 30–MHz IF, let us look at the VM–3 circuitry and discuss its operation.

VM–3 attenuator and signal calibrator. For our discussion, refer to the block diagram shown in figure 4-18. First, let's discuss the function of each circuit within the VM–3. Note that a stable 30-MHz signal generator source is in the VM–3. The chopped 30-MHz signal is alternately applied with a frequency accuracy of ±0.002 percent. It maintains an amplitude stability of ±0.005 dB/10 minutes. This 30-MHz signal is applied to an electronic switch, which is controlled by a 1-kHz, square-wave oscillator within the VM–3. The chopped 30-MHz signal is alternately applied through the standard attenuator to a signal-combining circuit. At the signal-combining circuit,

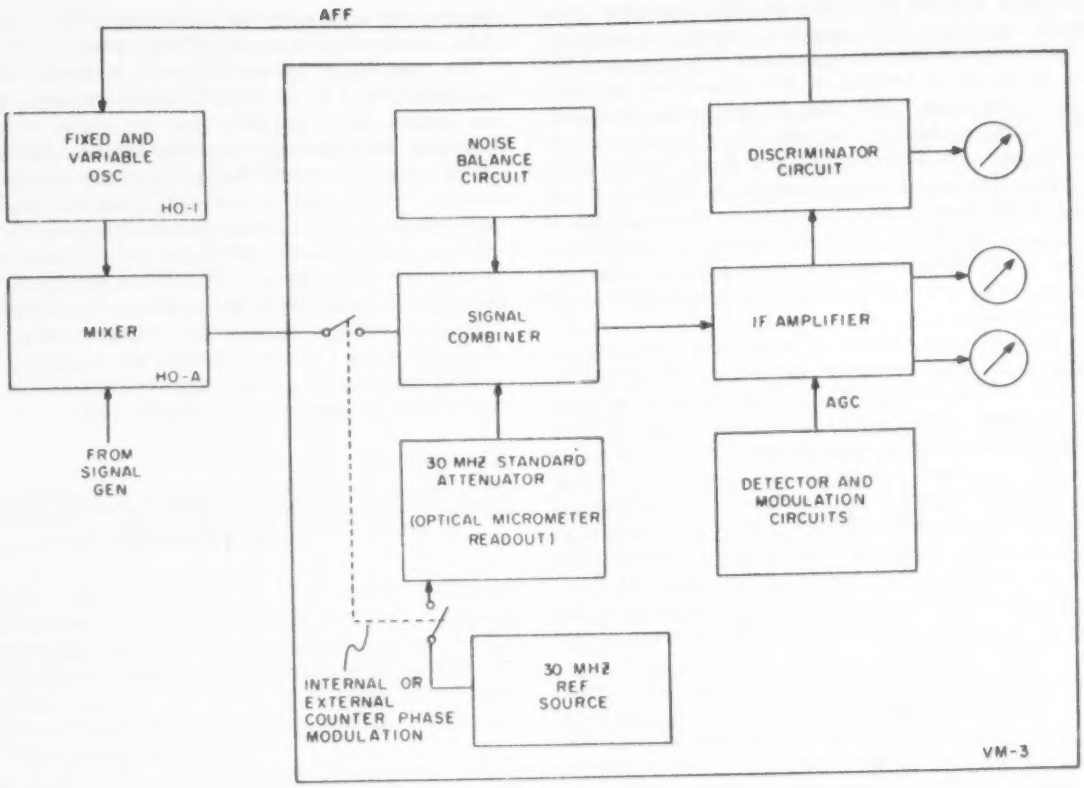


Figure 4-18. Block diagram HO-1, HO-A, and VM-3 setup (IF substitution).

the 30-MHz signal and the externally converted 30-MHz signal are in counterphase and applied to the IF amplifier.

Before we continue, let's go back and discuss the standard attenuator. The attenuator is the heart of the measurement system. This attenuator is a precision 30-MHz waveguide below cutoff attenuator. An attenuator of this type operates in the following manner.

An electromagnetic wave of a frequency lower than the lowest cufoff frequency of the waveguide is launched from a movable launching coil located at one end of the waveguide. This wave is then attenuated exponentially along the distance between the launching coil and a stationary receiving coil. The stationary receiving coil is located at the opposite end of the waveguide from the launching coil. Now, whenever a waveguide is operated below cutoff, an electromagnetic field is set up which decays at a very rapid but constant rate. At a fixed frequency of 30 MHz, this attenuation rate in decibels is a constant determined by the physical dimensions of the waveguide; and it can be very accurately calculated. Because of its simplicity and the fact that the change of attenuation can be directly related to physical distance measurement, this attenuator is an extremely useful and accurate standard.

Whenever attenuation measurements are made with the VM–3, the actual attenuation is measured between two settings of the waveguide below cutoff substitution attenuator. This measurement is made using an optical micrometer, which—instead of being calibrated in length—is calibrated in decibels.

The use of the optical readout device eliminates the problems of backlash and lead screw calibration. Separation between the launching and receiving coils is controlled both by a coarse rack and pinion and an independent fine control. The optical device eliminates any problems of wear in the drive mechanism and reads the movement of the coil to an accuracy of 0.0001 inch. The entire attenuator and optical assembly can be easily removed for calibration.

Note in figure 4-18 that a noise generator output also is fed to the signal combiner. This generator introduces a generated noise to circuit. When the VM–3 is operated with CWRF source, the 30-MHz IF signal which is applied to the input of the VM–3 is internally chopped at a 1-kHz rate. The phase relationship between this 1-kHz diode switch and the 1-kHz diode switch in the 30-MHz source is such that during one-half of the cycle, the signal from the internal 30-MHz standard is on. During the other half of the cycle,

the external 30-MHz IF signal is on. This means that noise from the mixer crystals is present only during the portion of the cycle when the external signal is on. The absence of this noise signal during one-half of the cycle is not important unless levels below −80 dBm RF are being measured. However, below this level the absence of this mixer noise does become very important because the signal and noise are comparable in amplitude. When the operator adjusts the output of the internal 30-MHz attenuator for a balance, if the noise in the two halves of the cycle is not the same, a balance of the detected output does not represent a balance with the signal portion of the input. The error at about −110 dBm is approximately 1 dB.

To overcome this problem of noise when using internal switching, a noise generator and noise balance control circuit is employed in the VM−3. This circuit is adjusted from the front panel by means of a zero signal balance control prior to making a measurement. The noise from the generator is injected into the system during the one-half cycle when the external IF signal is cut off. The switching is done electronically with the diodes. They are arranged on the circuit so that when one diode receives a forward bias and is on, the other diode receives a back bias and is off. This circuit now offers a balance or a cancellation of the mixer noise present, thus increasing the accuracy of low levels of measurement.

From the signal combiner, the combined signals—which include the 30-MHz reference, the 30-MHz IF signal, and the generated noise—are fed to the 30 MHz IF amplifier. The IF amplifier serves only to detect a difference between two signals. Its gain is critical only so far as overall range and sensitivity are concerned. To keep the output indicator sensitivity constant over a wide range, AGC is applied to the cathodes of four stages of the amplifier.

The IF amplifier has two video detectors. One detector provides AM output which is applied to the AGC circuit, to the amplitude balance and metering circuits, and to a cathode follower which is DC-coupled to the AM output connector on the front panel. The other detector provides an output at an external jack for use with an external VSWR indicator or recorder.

The 1-kHz component from the detector in the IF amplifier is applied to the amplitude comparator circuit through an amplifier to a synchronous detector. The two deflection plates of the synchronous detector receive a coherent 1-kHz reference signal from the reference amplifier whose input is generated by the 1-kHz source of the VM−3. The amplitude balance null indicator is connected across the two plates of the synchronous detector and indicates any unbalance in amplitude between the external 30-MHz IF signal and the internal 30-MHz reference signal. The use of a synchronous detector in this circuit enables measurements to be made at much lower levels with influence of noise, since it responds only to coherent signals.

You can adjust the amplitude balance meter for an electrical zero by depressing a zero adjust button which shorts the grids of the synchronous detector to ground and by adjusting the zero adjust control for a null indication. The zero adjust control adjusts for an equal current through both plates of the synchronous detector; the sensitivity of the meter is adjusted by the sensitivity control, which is a 500k potentiometer in series with the meter.

To compensate for the effects of frequency drift and incidental FM of the 30-MHz difference frequency between the tunable local oscillator and the signal source, an interdependent automatic frequency follower (AFF) circuit exists between the HO−1 tunable oscillator and the VM−3 receiver. The VM−3 receiver produces a voltage proportional to the frequency difference between the IF and 30-MHz standard source within the VM−3. This correction voltage is fed through the AFF cable to the repeller of the tunable oscillator. With the feedback loop closed, this correction voltage changes the repeller voltage of the oscillator which, in turn, changes the frequency of the tunable oscillator to maintain equality between the IF and the 30-MHz reference source within the VM−3.

Exercises (653):

1. Using the IF substitution method, describe briefly how an attenuation measurement is made.

2. What type of mixing is employed for input frequencies of 4.15 to 12.4 GHz? How are these mixing frequencies controlled in the HO−1?

3. What output must be provided at the HO−A input to provide full utilization of the VM−3 receiver?

4. Identify the three major elements used in the IF substitution method and describe the function of each element.

5. State the standard attenuator and readout used in the VM−3.

6. What is the purpose of the noise generator circuit in the VM−3?

7. What are the purposes of the two video detectors in the IF amplifier of the VM-3?

8. Where is the signal used to detect the amplitude difference of the 30-MHz IF and the 30-MHz reference signal developed?

9. How are frequency drift and incidental FM of the HO-1 corrected?

654. State the function, frequency range, and applications of the Micro Tel Model 1295 Precision Attenuation Measurement Receiver.

Micro Tel Model 1295 Precision Attenuation Measurement Receiver. The Model 1295 is a completely self-contained receiver for manual and semi-automatic, NBS-Traceable attenuation measurements covering the frequency range of 10 MHz to 40 GHz. It includes provisions for operating under IEEE-488 Bus Control and with a frequency synthesizer.

The Model 1295 receiver provides fundamental mixing over its entire frequency range, digital averaging of the received signal level, automatic calculation of attenuation level, and a precision IF attenuator. The IF attenuator is adjustable over a small range and is calibrated against a 30-MHz reference atttenuator. A 30-MHz reference source is part of the receiver.

The Model 1295 receiver has the capability to calibrate fixed or variable attenuators using an external signal source, calibrate the output attenuators of signal generators, and to calibrate standard noise sources using an external standard noise source and associated components. The instrument also operates as a 30 MHz IF Receiver.

Exercises (654):

1. What is the frequency range of the Model 1295 receiver?

2. How is the IF attenuator calibrated?

3. Over what range of frequencies does the Model 1295 receiver provide fundamental mixing?

655. List the circuits of the Micro Tel Model 1295 Precision Attenuation Measurement Receiver and state their functions.

RF Tuner and Pin Switch. The RF tuner converts the incoming RF signal to the first IF of 30 MHz. For convenience, the tuner can best be explained by considering three different frequency ranges. For all ranges, the local oscillator signal is obtained from one of two switched YIG oscillators which together cover the frequency range of 2 to 18 GHz, plus and minus the 30 MHz IF offset. The pin switch modulates the noise input with a 1-KHz squarewave from the 1 KHz ramp generator when used in the noise function.

NOTE: Refer to figure 4-19 for the simplified block diagram of the Model 1295 receiver.

The two oscillators are switched to a single mixer to cover the range of 2 to 18 GHz. From 18 to 26.5 GHz, the mixer is external and contains an integral doubler. It connects to the receiver through two coaxial cables, one for the local oscillator and one for the IF, and a diode bias cable. From 26.5 to 40 GHz, the mixer is also external and contains an integral tripler. The mixers from 18 to 40 GHz, with internal multipliers, provide the sensitivity of fundamental mixing without additional local oscillators. This technique entails some sacrifice of high level linearity, but is advantageous in that the local oscillator can be synthesized with a standard synthesizer. Up-conversion is used to cover the range of .01 to 2 GHz. The local oscillator heterodynes the incoming signal to an intermediate frequency of 2.33 GHz, which is then converted to 30 MHz.

IF Amplifier, Video Detector, Automatic Frequency Control (AFC), Voltage Controlled Oscillators (VCO), and 1-KHz Ramp Generator. These circuits amplify the incoming 30 MHz CW signal, modulate it at a 1-KHz rate, detect the modulated signal both with a square-law and crystal detector, and generate an electronic AFC voltage.

The incoming 30-MHz IF signal is amplified to drive the second mixer. The local oscillator signal to this mixer is centered at 40.7 MHz that is frequency modulated at a 1-KHz rate. The deviation is about four times the selected 3-db bandwidth of the following 10.7-MHz amplifier. The bandpass response of the 10.7-MHz amplifier is approximately Gaussian (Gaussian—a theoretical frequency distribution used in statistics that is bell-shaped, symmetrical, and of infinite extent.) Therefore, the output from this amplifier is amplitude modulated at a 1-KHz rate, and its envelope approximates a sine wave.

If the frequency of the incoming CW signal drifts from the center value, the phase of the detected sine wave will shift with respect to the phase of the sawtooth sweep. Thus, by comparing the phases of the sawtooth sweep and the detected IF in a phase detector, a DC error-correction voltage is generated. It is amplified, filtered, and fed back to the VCO to retune it so that the IF is recentered in the 10.7-MHz bandpass. In the manual tuning mode, this AFC voltage drives the tuning motor, which is located in the RF tuner, through a clutch if the voltage exceeds preset limits. Therefore, in the manual mode, the receiver will follow a slowly drifting signal across the full band.

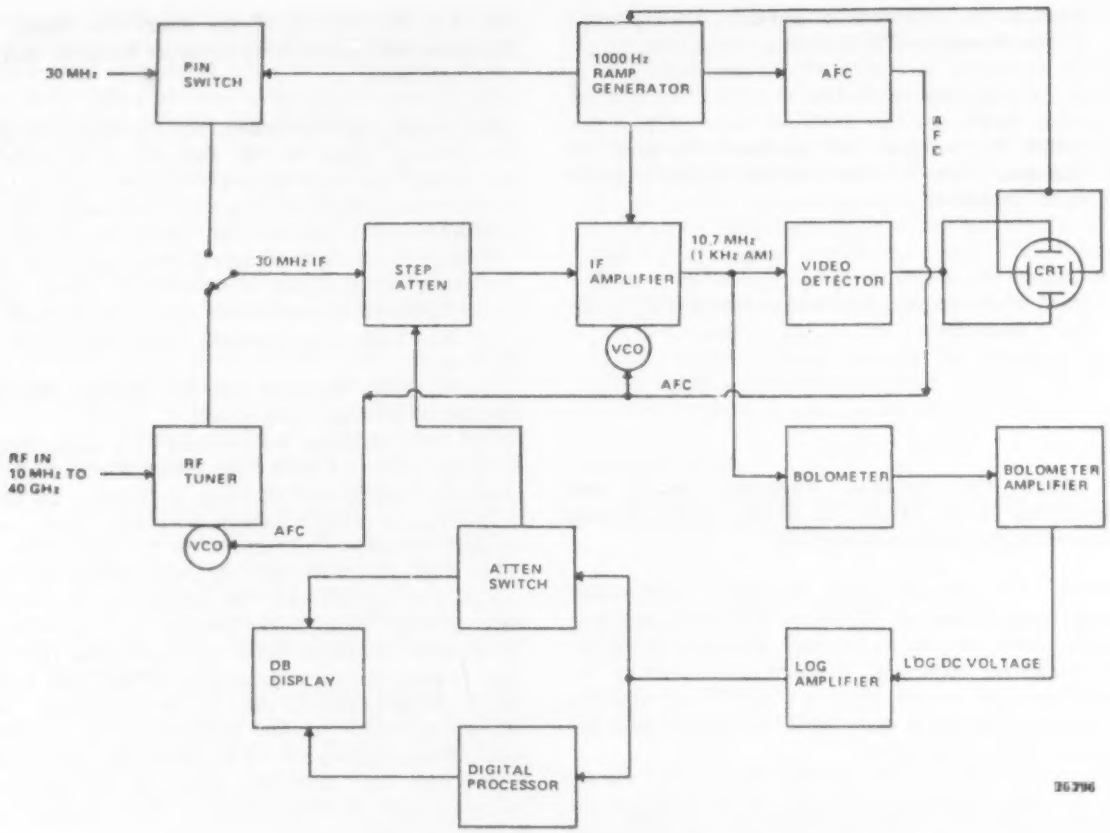


Figure 4-19. Model 1295 receiver block diagram.

Step Attenuator. The 30-MHz signal connects through the step attenuator to the IF amplifier. The step attenuator has eleven 10-dB steps for a total range of 110 dB. Each 10-dB step is adjustable through the receiver front panel so that it may be set precisely to 10 dB by reference to an external standard reference attenuator.

Bolometer, Bolometer Amplifier, Log Amplifier, Attenuation Switch, Digital Processor and DB Display. The bolometer is a square-law device so the 1-KHz voltage at its output is proportional to the input power. This 1-KHz voltage is amplified, detected, and logged by the bolometer amplifier and the log amplifier to develop a DC voltage proportional to dB power change over a range of 13 dB. If the level change exceeds 10 dB, the attenuator switching logic switches 10-dB attenuator steps to re-establish the LOG DC voltage within a 13-dB window. The LOG DC voltage is digitally averaged by the Digital processor. This voltage is added to the inserted attenuation value (10-dB increments) to drive the front panel dB display to a resolution of .001 dB over 123 dB.

CRT Display. The CRT display is a spectrum analyzer whose horizontal plates are driver at 1 KHz by the 1-KHz ramp generator. The vertical plates respond to the amplitude of the detected 10.7 MHz IF that is amplitude modulated by 1 KHz. The display then is a Gaussian pulse centered at the IF frequency when the receiver is locked to the RF Input.

Exercises (655):

1. How is the local oscillator signal obtained?

2. How is the mixer signal obtained when the receiver is used between 18 and 40 GHz?

3. What is the center frequency of the local oscillator signal to the second mixer?

4. How is the DC error-correction voltage generated?

5. What is the range of the step attenuator in dBs?

6. What is the relationship of the input power to the Bolometer to its output voltage?

7. What is the resolution of the Model 1295 receiver?

8. What is the frequency of the detected signal that is applied to the vertical plates of the CRT display?

4-4. Swept Frequency Attenuation Measurements

The development of the backward-wave oscillator has led to a new and faster technique for making measurements in the microwave frequency region. In the past, the mechanically-tuned klystron was used for this band of frequencies. Among the disadvantages of the klystron was the difficulty in mode-switching and tracking, long sweep times, wear involved in mechanical tuning, and the time involved in making measurements across a band of frequencies. These disadvantages are overcome with the use of swept frequency techniques.

656. State the function of the PIN diode attenuator in a sweeper system; define "pulling"; and indicate how the PIN diode attenuator helps to maintain the BWO constant in the system.

Leveling Circuit. Swept frequency, as the name implies, means that the generator will sweep between two frequencies. This is accomplished by sawtooth modulation of the output of a backward-wave oscillator.

In a previous discussion, you learned that the output frequency of a BWO is controlled by the helix potential. If a sawtooth waveform is applied to the helix, it can be seen that the output frequency will change at the sawtooth rate. The range of frequencies that will be swept will be dependent upon the amplitude of the sawtooth.

An undesirable effect on the output of a sawtooth-modulated BWO is that the output power increases as the frequency increases. In earlier sweep generators, this increasing power was corrected by using a feedback loop for automatic power leveling. The generator output was sampled through a directional coupler, converted to a DC voltage, and fed back to the BWO helix. Therefore, a change in output power would create a corresponding change in the helix voltage to correct the power. But this system also had a disadvantage. The DC correction voltage applied to the helix would make an unwanted change in output frequency. To prevent this frequency "pulling," the BWO output would have to be maintained at a constant power level across the frequency band, without a direct feedback to the BWO.

The PIN diode attenuator serves this purpose in a sweeper system. The PIN diode is a PN junction separated by an intrinsic layer of material. At frequencies below 200 MHz, the PIN diode will pass a signal without altering its shape. However, by varying the diode bias voltage, we can change its impedance. Thus, we now have an electronically controlled variable attenuator.

The PIN diode attenuator can be placed on the output of the BWO, and the DC voltage developed in the leveling loop can be applied as bias to the PIN attenuator. In this way, the output power is held constant without frequency "pulling."

A basic leveling loop, using a PIN attenuator, is shown in figure 4-20. The DC level for biasing the PIN attenuator comes essentially from two control circuits. The power level adjust sets the initial bias and the ALC gain control determines the amount of DC control voltage change for a given BWO output power change. The end result is a leveled RF output across the entire band of frequencies.

Exercises (656):

1. What is meant by the term "pulling" as it applies to leveling of the BWO output?

2. Why is the PIN diode sometimes referred to as an electronically controlled, variable attenuator?

3. How does the PIN diode attenuator help to maintain the BWO output constant in a leveled sweeper system?

657. Specify how the horizontal axis of the X–Y recorder chart is made to indicate frequency units; state what drives the Y axis pen; and define output level.

X–Y Recorder. A device frequently used in swept measurements is the X–Y recorder. The X–Y recorder operates on the same principle as does an oscilloscope. A sawtooth waveform is applied to the X axis input of the recorder to drive a pen assembly from left to right, across a chart. The same sawtooth which modulates the BWO helix is used to drive the recorder X axis. In this way, the horizontal plot on the chart is calibrated in frequency units per division.

The Y axis of the recorder receives its input from the detected RF power output of the generator. The detected RF power is converted to a DC voltage before being applied to the X–Y recorder and is representative of the power output of the generator. The final result is a plot of power output versus frequency. Both the X and Y axes of the X–Y recorder have variable sensitivity controls to allow the operator to calibrate the charted information.

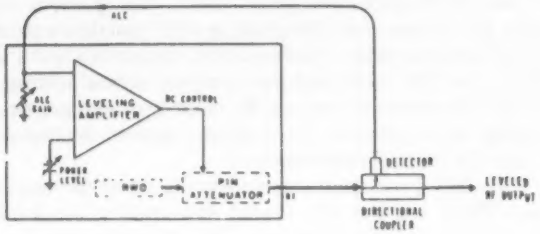


Figure 4–20. Basic leveling circuit.

Exercises (657):

1. How is the horizontal axis of the X–Y recorder chart made to indicate frequency units per division?

2. What drives the Y axis pen of the X–Y recorder?

3. What is represented by the final output of the X–Y recorder?

658. Cite the purpose of the preinsertion procedure; explain what is represented by the recorder output of the SWR meter; and tell the purpose of the grid lines and the final chart from the X–Y recorder.

Sweeper System Operation. The common method of attenuation measurement, using a swept system, involves two separate procedures. As in any insertion technique, the system itself must first be calibrated. The system calibration is called RF preinsertion.

For the purpose of explanation of this technique, we will assume that we are to calibrate a 10 dB, X-band attenuator, to an accuracy of ±1 dB. (X-band is 8.2 to 12.4 GHz.) To calibrate this attenuator we will compare it to a calibrated variable attenuator such as the X–382. The equipment setup will be as shown in figure 4-21. Notice that figure 4-21 shows the leveling loop (ALC) being fed back to the sweep oscillator. This will give us a leveled RF output at the main arm of the directional coupler. We can assume that the generator is set to sweep a band of frequencies from 8.2 to 12.4 GHz. Also notice that the X input to the X–Y recorder is connected to the sweep output from the sweep oscillator. The horizontal axis of the recorder is now a plot of frequency.

Returning to the leveled RF output, the line marked CALIBRATE indicates that the test device is not in the line at this time. There is a direct connection between the directional couplers. The auxiliary output of the second directional coupler is detected and fed to a standing-wave indicator, through a variable attenuator. The recorder output of the SWR indicator is a DC voltage comparable to the voltage which drives the SWR meter. This DC voltage is the input to the Y axis of the X–Y recorder. Therefore, the Y axis is now representative of whatever power level is at the output of the variable attenuator.

To begin the RF preinsertion, the X–382 is set to 10 dB, and the SWR meter controls are set for an on-scale indication. The Y-axis controls on the X–Y recorder are set so that the pen is approximately centered. Since we desire to calibrate the attenuator to 10 dB ±1 dB, we must now adjust the Y axis of the recorder so that the chart will indicate a 2-dB change from top to bottom of the chart. This is done by setting the X–382 to 11 dB and adjusting the Y zero control so that the pen is at the bottom of the chart. Then, the X–382 is set to 9 dB, and the Y sensitivity controls are adjusted so that the pen is at the top of the chart.

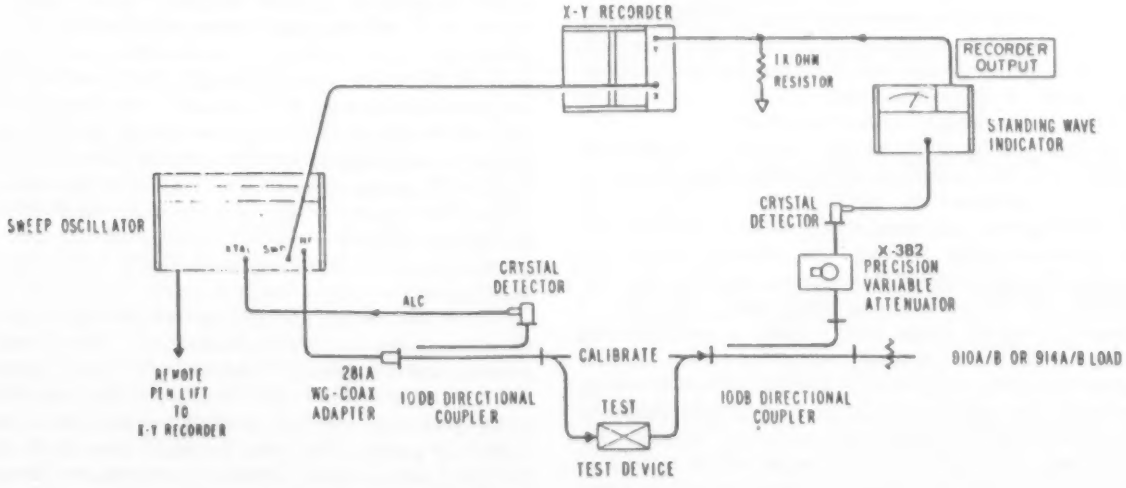


Figure 4–21. RF preinsertion technique for swept attenuation measurements.

With the X–Y recorder now calibrated to represent the power on the line within a 2 dB range around 10 dB, we are now ready to draw some grid lines.

First, set the X–382 to exactly 9 dB. The sweep oscillator will be in the triggered mode, which is similar to the single sweep operation of a scope. Place a sheet of chart paper on the X–Y recorder, and press the trigger button of the sweeper. The sweeper will now begin to sweep from 8.2 to 12.4 GHz one time, and then return to 8.2 GHz. During this one-time sweep, the X–Y recorder is being driven from left to right at the same rate as the sweeper, and the vertical axis is being driven by whatever power level is present at the output of the X–382. The pen on the recorder will draw a line on the chart paper representing a plot of power versus frequency, at the 9-dB setting of the variable attenuator.

The X–382 is now increased in 0.2 dB increments, until a setting of 11 dB is reached. At each increment, a new sweep is triggered and a line is drawn on the chart to represent power versus frequency at that increment. The end result on the chart paper is a series of grid lines on the chart representing a 10 dB ±1-dB setting of the X–382 attenuator.

The X–382 attenuator is set to 0 dB, and the test instrument is inserted between the two directional couplers. Since we have removed about 10 dB from the X–382 and inserted 10 dB in the line, the power at the output of the X–382 should be at approximately the same level as before.

It would be convenient at this time to change the color or the pen in the X–Y recorder so that the new color will represent the test instrument.

The sweeper is now triggered and a line drawn on the chart to show the power versus frequency plot of the 10-dB attenuator. As long as this line stays within the limits we drew with the X–382, the attenuator meets specifications. If it does not, we have permanent record of what frequency does not meet specification, and also a correction chart that can be sent to the using organization.

Although this discussion has only dealt with attenuation measurement similar techniques can be employed with the sweeper system to measure impedance, power, and frequency.

Exercises (658):

1. What purpose is being served by performing the preinsertion procedure?

2. In the sweeper setup, what is represented by the output from the recorder output of the SWR meter?

3. What is the purpose of the grid lines drawn during preinsertion?

4. Of what use is the final chart from the X–Y recorder?

CHAPTER 5

Microwave Accessories

IN THIS CHAPTER, we discuss microwave accessories, such as terminations, tuners, slotted lines, and directional couplers, with which you must become familiar. Some of these items have been mentioned in previous chapters of this volume. In some cases, the items were incorporated in a microwave setup like you will be required to use in the PME laboratory. However, the theory of the items was not discussed at the time they were mentioned. For this reason, we will discuss the theory now in order to give you a better understanding of these items so that you can use them more proficiently when making calibrations or adjustments in the microwave setup.

5-1. Terminations for Coaxial Lines and Waveguides at Microwave Frequencies

Recall, from the previous chapter, that the design of dissipative attenuators involves two problems of paramount importance: (1) the choice of the material in which the power is to be dissipated and (2) the problem of matching the attenuator impedance to the impedance of the transmission line. These problems must also be solved in the design of a termination for a transmission line that will absorb all the line power without reflection. The design of a termination is often simpler than that of an attenuator because the impedance matching need be done at one end only. This section is devoted to the knowledge of terminations you should possess to increase your proficiency in the microwave area.

659. Name the two common classes of terminations; cite their differences; and solve problems regarding functions of matched transmission line terminations.

Matched Transmission Line Terminations. There are innumerable applications in microwave work for matched impedance transmission line terminations, or loads, as they are more commonly called. The number of materials and designs used in terminations is as great as the number of applications. Terminations are commonly classed as either (1) high-power or (2) low-power terminations. High-power terminations are designed to take the full output power of a transmitter tube; that is, power ranging from a few watts to several hundred watts. High-power loads are usually required to have a VSWR not greater than 1.05 or 1.10.

As opposed to the high-power loads, the low-power loads of a transmission line are normally broken down into two classes. Some applications demand that the loads be almost perfectly matched; that is, their VSWR would be no greater than 1.01 or 1.02. Impedance measurements on lossless or low-loss components are often conducted with a matched line termination placed after the component under test, and such a termination should have a VSWR of no more than 1.01. In contrast, the terminations used in the secondary lines of directional couplers, for example, can often be allowed a maximum VSWR as great as 1.1 or 1.2. In this application, a compromise is usually necessary between the allowable VSWR and the allowable physical dimensions of the termination, with the directivity of the directional device being the determining factor in setting the maximum allowable VSWR. Low-power loads are seldom designed to dissipate more than 0.5 watt.

In the design of a line termination, there are a number of factors which you must consider. The most important electrical considerations are (1) the maximum allowable VSWR and (2) the bandwidth over which the VSWR specification is to be met. The maximum safe power capacity of the load is also of considerable importance. For high-power loads, it is necessary to consider both average power dissipation and pulse power breakdown, or "arc-over." The impedance match should be independent of temperature within the stated safe average power limit, and this impedance match should not be affected by humidity variations or by aging. Many applications demand that the loads be very carefully protected against RF leakage. The impedance match of the load should be quite insensitive to shock and vibration. The size, primarily the length, of the termination is also important in some applications. In constructing well-matched loads (VSWR less than 1.02), it is of particular importance that precision waveguides or coaxial lines be used. The reflection from a small discontinuity at the junction of the load and the line which it terminates can easily account for a VSWR of 1.01 or 1.02.

The metal housing for the load is customarily terminated by an RF short circuit to avoid RF leakage from the load. This imposes a lower limit on the attenuation of the termination if a broadband impedance match is to be obtained. Figure 5-1 and the following calculations show that the VSWR of a short circuit, measured through 23 dB of matched attenuation, is 1.01.

$$\gamma = \frac{pr}{\sqrt{\pi}}$$

where

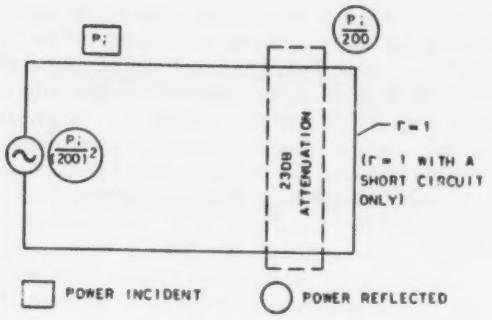


Figure 5-1. Effect of load on VSWR.

γ = reflection coefficient

pr = power reflected

pi = power incident

Therefore, referring to figure 5-1, we can proceed with the computation as follows:

$$\gamma = \sqrt{\frac{pr}{pi}}$$

$$= \frac{\frac{pi}{(200)^2}}{\sqrt{\frac{pi}{1}}}$$

$$= \frac{1}{(200)^2}$$

$$= \frac{1}{200}$$

$$= .005$$

Now we have the γ of the circuit; however, we want the VSRW. To obtain the VSWR, we proceed as follows:

$$VSWR = \frac{1+\gamma}{1-\gamma}$$

$$= \frac{1+.005}{1-.005}$$

$$= \frac{1.005}{0.995}$$

$$= 1.01$$

The computations, therefore, prove that the VSWR of a short circuit measured through 23 dB of matched attenuation is 1.01. Since the termination is not likely to be exactly matched, it is essential to have a minimum of 30 dB of attenuation in the load if there is to be any hope of obtaining a load VSWR less than 1.01 over a wide range of frequencies. (The theoretical VSWR of a short circuit measured through 30 dB of attenuation can be computed by using the formulas given, and it will be approximately 1.002.)

Exercises (659):

1. What are the two common classes of terminations? How do they differ?

2. Assume that we have short circuit with a γ of 0.01. What is the VSWR value of the circuit?

3. What is the γ of a short circuit measured through 20 dB of matched attenuation?

4. What is the VSWR of a short circuit measured through 10 dB of matched attenuation?

660. Identify the electrical length and material used for low-power coaxial line terminations.

Low-Power Coaxial Line Terminations. A coaxial line termination has been developed which meets a maximum VSWR specification of 1.02 to 1.04 over an 8- to 10-percent band (4 to 5 percent on each side of the frequency for which designed). This design utilizes a thermo-setting plastic which is cast in a section of the line to be terminated. Then, because the temperature coefficient of expansion of the plastic is greater than that of the material used in the conductors, the plastic can be removed from the center conductor by heating and from the outer conductor by cooling. The plastic is a relatively easy material to machine, and a conical matching taper of the correct length can easily be made. The taper is carried all of the way to a knife edge at the center conductor, with the experimentally determined optimum taper length being approximately 2 wavelengths. The solid plastic provides a good support for the center conductor; consequently, the load is a rugged one.

Various polyiron materials have been used effectively in making 50-ohm step terminations in coaxial lines. Figure 5-2,A, shows a cross section of a polyiron cylinder used for a small diameter coaxial line. Figure 5-2,B, shows a preferable shape for a large diameter coaxial line. In the smaller size, the step shown in figure 5-2,A, would be so thin that it could easily be broken. Polyiron has the advantage of having a very large attenuation constant for microwaves; consequently, polyiron terminations can be made relatively short. Polyiron terminations can also be

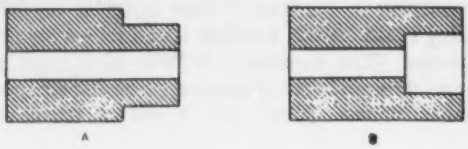


Figure 5-2. Cross section of polyiron cylinder for (A) small and (B) large coaxial lines.

made for use at wavelengths considerably longer than microwaves without becoming unwieldy.

Exercises (660):

1. What type of material is used for low-power coaxial line terminations?

2. In a low-power coaxial line termination using a conical matching taper as the energy absorbing element, approximately how long should the tapered element be if the termination is to be used at a frequency of 10 kHz?

661. Identify the characteristics, similarities, and types of waveguide terminations, and cite the best way to cause energy to reflect back from a waveguide ending.

Waveguide Terminations. Since a waveguide is a single conductor, its characteristic impedance (Z_o) is not as easy to define as is that of a coaxial line. Nevertheless, you can think of the characteristic impedance of a waveguide as being approximately equal to the ratio of the strength of the electric field to the strength of the magnetic field for energy traveling in one direction. This ratio is equivalent to the voltage-to-current ratio in coaxial lines on which there are no standing waves.

The lowest characteristic impedance of a circular waveguide is about 350 ohms. In a rectangular waveguide, the characteristic impedance may be any value, depending upon the dimensions of the waveguide and the frequency of the RF energy. However, the characteristic impedance in the rectangular waveguide is directly proportional to the narrow dimension when the other dimension and the frequency are fixed. In this type waveguide, the characteristic impedance may vary from nearly 0 to approximately 465 ohms.

There are a number of ways by which a waveguide can be terminated in its characteristic impedance. One way consists of filling the end of the waveguide with graphited-sand, as shown in figure 5-3.A. As the fields enter the sand, RF currents flow in it. These currents create heat. The energy is, therefore, dissipated as heat. None of the energy thus dissipated as heat can be reflected back into the waveguide. Another arrangement (fig. 5-3,B) uses a high resistance rod which is placed at the center of the E-field. The E-field passing through the rod causes current flow in the rod. The high resistance of the rod dissipates the energy as I^2R loss. Still another method for terminating a waveguide is to use a wedge containing high resistance (fig. 5-3,C). The plane of the wedge is placed perpendicular to the magnetic lines of force. When the magnetic lines cut the wedge, a voltage is induced in it. The induced voltage produces a current which, by flowing through the high resistance of the wedge, causes an I^2R loss. This energy, as in the previous methods, is dissipated in the form of heat. This dissipation permits very little energy to reach the closed end of the waveguide, and therefore, very little energy can be reflected. If these terminations are to be used as high-power loads, they are generally constructed with external fins to provide a larger radiating surface, and thus better heat dissipation.

Each of the preceding terminations is designed to match the impedance of the waveguide, in order to ensure a minimum of reflected energy. On the other hand, there are instances when it is desirable that all of the energy be reflected from the end of the waveguide. The best way to accomplish this reflection is to affix a permanent metal plate to the end of the waveguide, as shown in figure 5-4,A.

When it is necessary that the end be removable, a removable end plate is attached to the end of the waveguide. For this method to be satisfactory, the contact between the guide and the end plate must be exceptionally good, in order that the energy fields will not be attenuated by current flow. Perfect contact is not required when the connection is made at a point of minimum current. This point is located a quarter-wavelength from the end of the waveguide. When connection is made at this point, a cup is used instead of the end plate (fig. 5-4,B). The cup is a

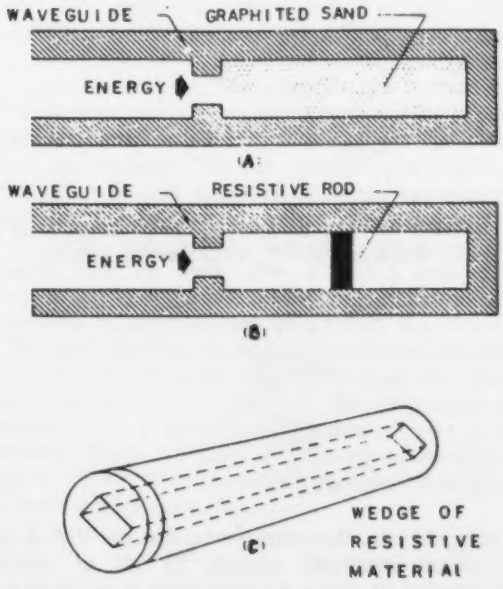


Figure 5-3. Terminations for minimum reflection.

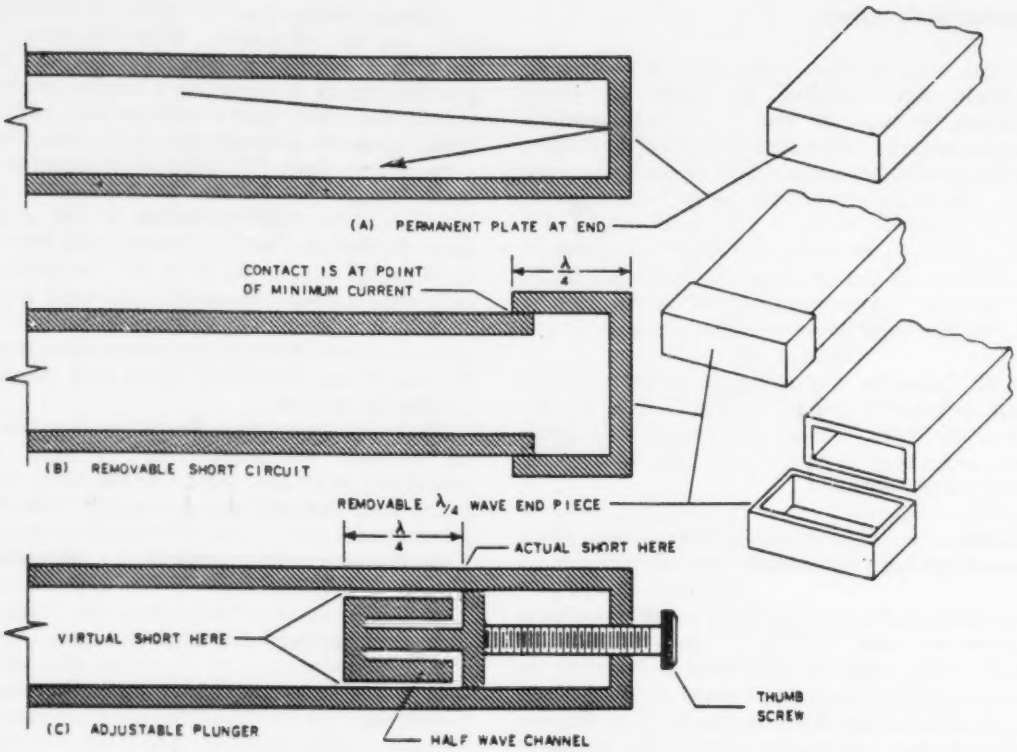


Figure 5-4. Terminations for maximum reflection.

quarter-wave long and is enough to fit over the end of the waveguide. The voltage between opposite sides of the cup opening is high, but as the reflected magnetic field cancels the incident magnetic field, the resulting current is very small and reflection is at a minimum.

When the end must be adjustable, the contact between the end and the waveguide must be nearly perfect. However, it is impossible to get a perfect contact. The best arrangement consists principally of an adjustable plunger which fits into the waveguide, as shown in figure 5-4,C. The walls of the waveguide and the plunger form a half-wave channel. The half-wave channel is closed at the outer end, and this channel reflects a short circuit where the current is minimum due to the standing waves. This minimum current makes it possible for the plunger to slide loosely in the waveguide at a point where the contact resistance to current flow is very low. An example of an adjustable termination is the HP Model 914A/B.

If you desire to find the reflection coefficient and/or the VSWR of a waveguide that is terminated in a fixed value, the same procedure can be followed as we have discussed earlier for coaxial line termination.

If you think over what we have said in this section, you can easily see that the materials used in, and the construction of, microwave terminations are very important considerations. Since you, as a PME technician, are mainly concerned with low-power terminations, this type of termination was covered more thoroughly than high-power terminations. By applying the principles which have been presented in this section, you should be able to visualize just how much a certain type of termination affects the VSWR of a microwave line. This will help you to select the proper termination to use when you are making microwave measurements.

Exercises (661):

1. What is the characteristic impedance of a rectangular waveguide proportional to?

2. What common property is possessed by most waveguide terminations?

3. What is the best way to cause all of the energy to be reflected back from the end of a waveguide?

5-2. Directional Couplers

Directional couplers have many uses in monitoring power levels and extending the range of power measurements, as well as numerous applications in reflectometer systems. This section is designed to increase your knowledge of directional couplers, so that you can use them more efficiently when making power measurements and monitoring power levels. A directional coupler is a device for sampling a fraction of the power flowing down a transmission line in one direction in preference to the opposite direction without disturbing the existing field in the line. This directional property of the coupler is called its directivity.

While the following explanation of theory regarding directional couplers is general in nature, it covers the operation of the Model 752 and other directional couplers you may come across as you expand your work in the microwave area of your lab.

662. Identify a directional coupler, and solve hypothetical problems regarding its operation.

Theory of Operation. A directional coupler consists of two sections—a main waveguide and an auxiliary waveguide—with a common wall which is shared by the two sections and which may be ajoined side by side or oriented at some angle. The coupling between the two waveguide sections is achieved by means of slots or holes in the common wall. One port of the auxiliary arm is terminated in a matched load.

The power flows down the main waveguide with a slight amount of attenuation. The amount of attenuation in the main guide is theoretically the amount of decoupled power in the auxiliary arm; however, wall and mismatch losses are included in the attenuation of the main guide. The decoupled power depends theoretically only on the power flowing in one direction in the main guide, and the power is extracted from the unterminated port in the auxiliary arm for monitoring purposes or for obtaining a lower level of power. However, due to imperfections in the coupler, a leakage signal from power flowing in the opposite direction in the main guide adds vectorially to the decoupled power in the auxiliary arm. The high directional property is obtained by using a series or an array of coupling holes. The matched load in the auxiliary arm absorbs power coupled from the reverse direction.

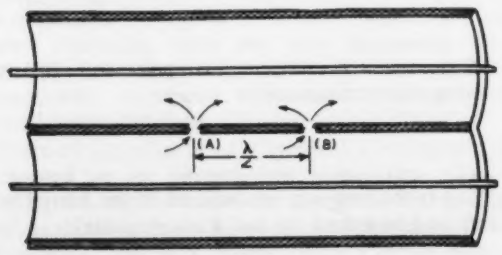


Figure 5-5. Two-hole coaxial coupler with coupling holes spaced λ/4 apart.

Although various types of coupling techniques are used (such as the cross-guide, Bethe-hole-type; multihole couplers; a side-wall coupling; and short-slot type), the principle can be illustrated by a coupler employing two coaxial lines which share a common wall, with two holes spaced a quarter wavelength apart for the design frequency.

Referring to figure 5-5, assume that a signal in the lower coaxial line is traveling from left to right. As a positive maximum of the signal passes hole A, part of the energy enters the upper arm and propagates in both directions from A. When the wave in the lower line reaches hole B, the same thing happens. Meanwhile, the wave in the upper line, which is propagating to the right, has kept pace with the main wave in the lower line so that it adds in phase with the field of the lower line, which goes through B and continues to the right.

The energy that travels to the left from B arrives at hole A just one-half wavelength later in time; therefore, cancellation of the field occurs for the energy propagating to the left. This provides the coupler with directional characteristics.

The following equations apply to any directional coupler. Refer to figure 5-6,A.

$$C = 10 \log \frac{P_1}{P_3} \text{ (coupling factor)} \quad \text{Equation 1}$$

$$L = 10 \log \frac{P_1}{P_2} \text{ (insertion loss)} \quad \text{Equation 2}$$

σ_1 and σ_2 are main line VSWRs, σ_3 is the auxiliary arm VSWR. Refer to figure 5-6,B.

$$I = 10 \log \frac{P_{2B}}{P_{3B}} \text{ (isolation)} \quad \text{Equation 3}$$

Where P_{2B} is power fed backward into port 2, and P_{3B} is power emanating from port 3 due to backward input P_{2B}.

$$I = C + D \text{ (in dB)}$$

$$D = I - C = 10 \log \frac{P_{2B}}{P_{3B}} - 10 \log \frac{P_1}{P_{3F}} \quad \text{Equation 4}$$

$$= 10 \log \frac{P_{2B}\, P_{3F}}{P_{3B}\, P_1} \quad \text{Equation 6}$$

If $P_{2B} = P_1$, Equation 5 becomes:

$$D = 10 \log \frac{P_{3F}}{P_{3B}} \text{ (directivity)} \quad \text{Equation 6}$$

The definitions are valid when all ports are terminated with matched components. The main-line VSWR and auxiliary arm VSWR must be measured with a matched generator and all other ports terminated in a matched load.

A directional coupler commonly found in the majority of PME's is the Model HP752( ) series. The Model 752 is a high directivity directional coupler used extensively in measurement systems in your lab.

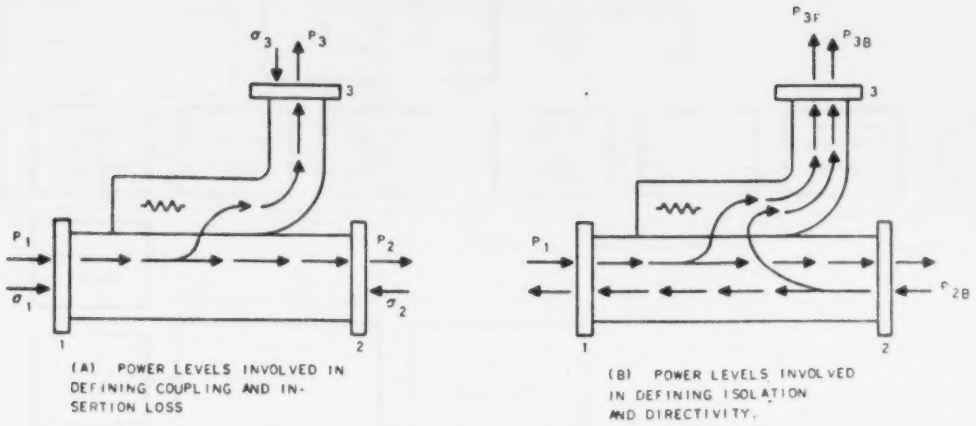

(A) POWER LEVELS INVOLVED IN DEFINING COUPLING AND INSERTION LOSS
(B) POWER LEVELS INVOLVED IN DEFINING ISOLATION AND DIRECTIVITY.

Figure 5-6. A representative diagram of a directional coupler.

The Model 752( ) series directional couplers cover several microwave operational bands. These bands will be designated by a letter prefix included in the part number of the directional coupler. For example, X752, the X indicates this directional coupler is designed to operate in the X band (8.2 to 12.4 GHz). Along with the letter prefix you will notice a letter suffix included in the part number.

The letter suffix indicates the degree of coupling or coupling factor. For example, the X752A is a 3-dB coupler that will operate in the X band. The letter suffix A indicates the coupler is a 3-dB coupler. Other suffixes are B for 6 dB coupler, C for 10 dB-couplers, and D for 20-dB couplers.

Exercises (662):

1. What is a directional coupler?

2. What is the directional property of a directional coupler called?

3. Referring to figure 5-6,A, if the power into port 1 of the directional coupler is 10 mW and the power out of port 3 is 1 mW, what is the coupling factor of the directional coupler?

4. Referring to figure 5-6,A, if the power into port 1 is 10 mW and the power out of port 2 is 8 mW, what is the insertion loss of the coupler?

663. Using the indicated measurement technique, compute the directivity of the coupler.

Measurement Technique. In measuring the VSWR of different ports of the coupler, the setup shown in figure 5-7 can be used. The port for which the VSWR is to be measured is connected to the slotted line with all other arms terminated in a matched load.

Coupling. If a single-channel, audio-substitution method is to be used for coupling factor measurements, the setup shown in figure 5-8 should be used. In performing this measurement, the preliminary procedure for source and bolometer mount tuning must be completed. A convenient reference level is then set on the output indicator, with attenuation set in the audio attenuator to a value slightly greater than the coupling value specified for the coupler.

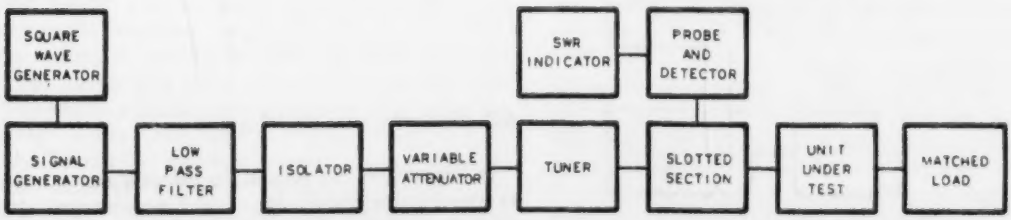


Figure 5-7. A typical setup for directional coupler measurement.

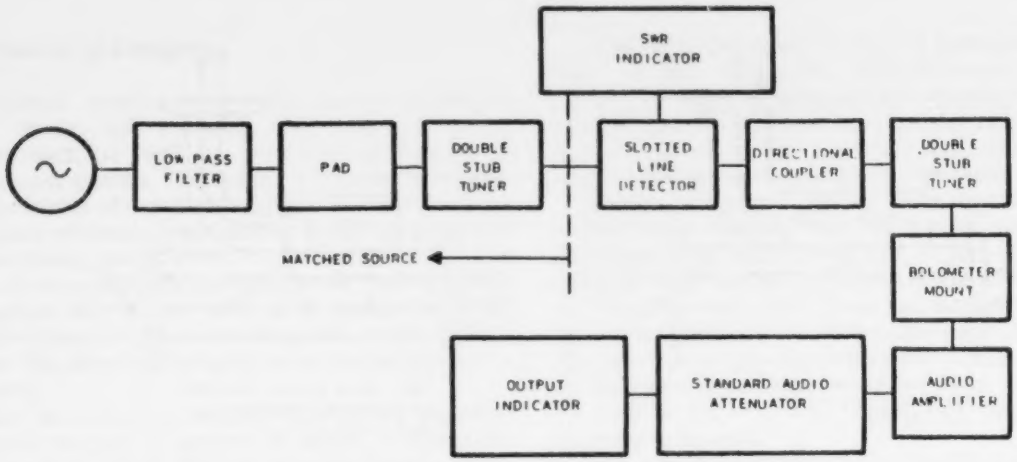


Figure 5-8. Coupling factor measurements.

Port 1 of the coupler is then connected to the slotted section on the load side. Port 2 of the coupler is terminated with a matched load, and the double-stub tuner with the bolometer mount is connected to port 3. The tuner should not be disconnected from the bolometer mount once it is tuned, since it becomes an integral part of the bolometer mount. In making this connection, the signal indicated on the indicator will decrease; therefore, the attenuation of the audio attenuator is decreased until the original level is restored on the indicator. The amount of attenuation removed is the coupling factor of the coupler.

Directivity measurements by direct attenuation measurements. In measuring directivity, the following connection, as shown in figure 5-9, should be made with reference to figure 5-8.

The attenuation from port 2 to port 3 is measured similarly to the coupling measurements. This attenuation measurement is equivalent to the isolation value defined in equation 4, with one exception. The isolation definition of equation 4 was based on the fact that the coupler was physically reversed for power input into ports 1 and 2. In this case, however, the coupler is fed into port 2 only; therefore, the insertion loss of the coupler is included. Thus, the isolation measured under this present condition equals

$$I = D + C + L \text{ (valid for power fed into port 2 only)}$$

The insertion loss L of the coupler must be measured; then the directivity equals

$$D = I - C - L$$

From what we said, you can see that the directional coupler can be used to extend the range of power-measuring equipment and to monitor power levels. Also, you should have gained a better understanding of how the directional coupler operates. Since you must know your equipment before you can use it properly, this section should help you in using and calibrating the directional coupler.

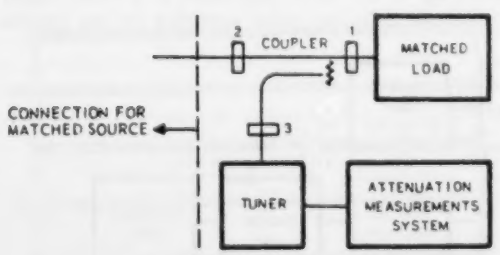


Figure 5-9. Setup for directivity measurements.

Exercises (663):

1. When power is applied in the forward direction through a directional coupler, the output from port 3 is 100 mW; however, when the direction of power is reversed through the coupler, the output power from port 3 is 0.01 mW. What is the directivity of the coupler?

5-3. Slotted Lines and Tuners

In this section, we present the information you will need to advance your knowledge of, and increase your ability in the use of, slotted lines and tuners when you are making VSWR measurements.

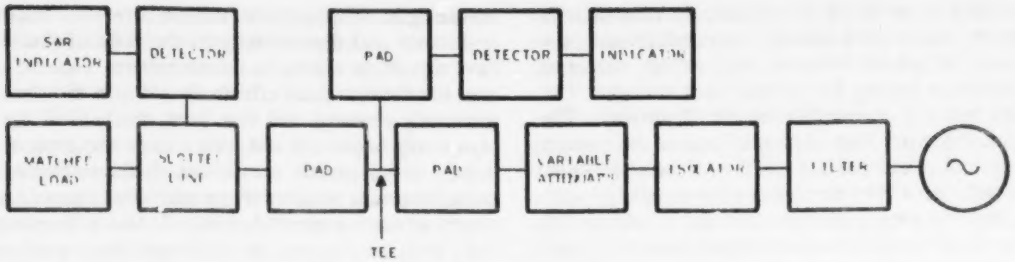


Figure 5-10. Block diagram for measuring structural defects of a slotted section.

664. State the purpose of slotted lines and their normal frequency range; and specify the purpose of the rotary-drum wave indicator.

Slotted Lines. A slotted line with a movable probe that accommodates a detector element is used in performing VSWR measurements. The slotted line is introduced between a modulated signal source and an unknown component in a matched system. In a matched system, the source and the terminating load (if the latter is required to terminate the component under test) are tuned for low VSWR. This tuning is normally accomplished by using one or more slide screw tuners inserted in the line. The principal use of the slotted line is to investigate the field distribution on the transmission line without disturbing the existing fields. A slotted line can be considered as a section of transmission line identical to the system transmission line where the standing waves are to be investigated. A narrow longitudinal slot, preferably several wavelengths long, is provided to accommodate a movable probe for sampling the field configuration. The slot is placed parallel to the lines of current flow, so that it will cause a minimum disturbance to the existing field. The probe is mounted on a movable carriage and samples the RF energy which is detected by a crystal rectifier or a bolometer.

Coaxial slotted lines are used for frequencies up to 10 kMHz. The coaxial section is rigid, with dielectric beads or resonant stubs used to support the inner conductor. The beads must be designed and carefully constructed to cause a minimum of reflections. Various types of rigid coaxial connectors are mounted on both ends for purposes of physically connecting with other coaxial components. The inner and outer conductors must be fabricated with precision and must be smoothly finished.

Another form of a coaxial slotted line is the parallel-plate type used in the frequency range from 0.5 to 4.0 kMHz. This type differs in construction from the aforementioned type in that, rather than using a narrow slot, the normally cylindrical outer conductor can be imagined to be formed as two parallel plates. The depth of probe penetration is inherently less critical, therefore, carriage inaccuracies are minimized. Leakage is also low, because the effective slot opening is small. Theoretically, the inner conductor should be elliptically shaped; however, it can be approximated with a circular form.

The carriage for the probe is mounted for horizontal movement at the top of the plates. The probe is located in the electric field, which decreases exponentially with distance from the center conductor. A metal rule is affixed to the line to indicate probe position.

Since the slotted line is customarily designed to support several wavelengths of a standing-wave pattern, the slotted line can become awkwardly long at the lower frequencies. In order to overcome this problem, a rotary-drum type of standing-wave indicator was successfully designed. A commercially available unit is the PRD–219. It is basically a coaxial T-junction, with a pickup probe assembly and a normalizing standard reactance. The probe assembly is manually operated. An external oscillator is required to supply an amplitude-modulated RF signal to the T-junction. The standard reactance is calibrated from 100 to 1000 MHz and is set for the appropriate operating frequency. The currents in the T-junction depend upon the impedance to be measured, and they determine the field configuration set up in the junction. The electric field intensity is a function of the radial angle of the rotary pickup probe. The probe houses a crystal which is used for detection. The detected output is a voltage which varies at the audio frequency of the applied modulating signal. The amplitude of the output voltage varies with the rotation of the probe. An external SWR amplifier is used in conjunction with the rotary-drum line for VSWR measurements.

The angle of voltage-reflection coefficient, referenced to the center of the T-junction, is obtained by rotating the calibrated drum to the nearest minimum output position and then reading the dial. The angle may be obtained with reference to any other plane, such as the end of the center conductor of an unknown impedance.

For the VHF and UHF ranges, admittance meters are used with success in measurements of impedance and admittance. One commercially available instrument in the UHF range is the General Radio Type 1602. It is a null-type device for determining the admittance of components for coaxial systems. The GR–1602 has an indicator for adjusting a network to a predetermined admittance or for matching one network to another. The GR–1602 also can be used to determine magnitudes of impedance and reflection coefficients as well as VSWRs.

Essentially, the GR–1602 comprises a coaxial line to which the unknown is connected, a shielded pickup loop for

current sampling, a second line and loop terminated in a pure resistance, and a third line and loop terminated in a pure reactance. All are fed from the same voltage source to maintain coherence among the several input voltages. The current in each line is proportional to the admittance. The voltage induced in each loop is proportional to the current in the corresponding line and is a function of the orientation of the adjustable loop. The three loops are paralleled, and the voltage from the loop in the unknown line is canceled by adjusting the loops coupled to the standard lines for a null condition. The conductance and susceptance of the unknown are directly readable from the scales of the standard loops.

Exercises (664):

1. What is the purpose of slotted lines?

2. What is the normal frequency range for coaxial slotted lines?

3. What is the purpose of the rotary-drum type standing-wave indicator?

665. In the operation of waveguide slotted lines, explain how to prevent error in measurement, and identify the part which reduces errors.

Waveguide Slotted Lines. In the waveguide slotted line, a section of waveguide is slotted along the center of the broad wall. Attention must be paid to probe penetration, slot-end reflections, and tolerances of dimensions in slot width. Because of the absence of the inner conductor, fabrication is simpler and problems of reflections caused by supporting beads are nonexistent. The top surface is precision-machined to ensure smooth movement of the carriage with a probe assembly. Some of the commercial units are provided with a dial indicator as well as a metal rule to determine accurately the probe position. The probe currents return to the waveguide through the capacitance of the narrow gap, which separates the carriage from the waveguide section. In order to prevent the occurrence of unwanted resonances from the capacitance and the external parts, a low-impedance resonant trap at the outer conductor of the probe or a highly glossy material (e.g., powdered iron) is used.

Accuracy and source of error. The slot effect on a slotted line may be small in a well-constructed line. However, the slot effect must be taken into account in accurate measurements. The slot's principal effect is the reduction of the capacitance per unit length of the line. The reduction of capacitance causes a small increase in the characteristic impedance. In the case of a waveguide slotted section, this effect results in a slight increase in the guide wavelength. Reflections caused by the change in impedance and discontinuity at the ends of the slot may have significant effects on measurements. Tapered slots are used to minimize these effects. In addition, the slot must be accurately centered and free from mechanical defects or asymmetry to prevent slot waves from being excited. One treatise on microwave measurements shows that the probe assembly can be replaced by an equivalent shunt admittance placed across a transmission line. It also is shown that the shifts from the true positions of the minimum and maximum values of the standing wave depend primarily on the shunt susceptance alone. If the shunt susceptance is zero, no shifts occur—regardless of the magnitude of the probe shunt conductance. Consequently, it is important to use a tunable probe which is capable of reducing the susceptance to zero. The error in the VSWR reading due to pure conductance is given by

$$\frac{\sigma_m}{\sigma} = \frac{1 + \sigma + G_p}{1 + \sigma + G_p}$$

where σ and σ_m are the true and measured VSWRs, respectively, and G_p is the normalized probe conductance. In measuring the VSWR, the probe insertion should be kept at a minimum in order to reduce G_p. The generator also should be well matched and isolated so that the power from the generator will not be a function of the probe position. If the power were a function of the probe position, an apparent standing wave would be indicated by the probe, even if the line were terminated by a perfectly matched load.

Measuring structural defects of a slotted section. Very informative tests on the structural part of a slotted section can be made rather simply. These tests can be performed by terminating the end of a slotted section with different values of reflection coefficient and by taking extensive data on the voltage distribution as a function of probe position. If the data is taken for opposite directions of probe travel and the information plotted, any irregularity in the pattern (i.e., deviation from a sinusoidal pattern and noncoincidence of patterns for opposite travels of the probe) can disclose information on the characteristics of the line, such as the possibilities of an off-centered slot and undesirable mechanical play between the slot and the probe carriage. The block diagram for measuring structural defects of a slotted section is shown in figure 5-10.

The procedure for making such measurements is as follows:

a. A convenient signal reference level is established at the detector, using a sensitive scale of a milliammeter as an indicator.

b. The response readings of the SWR indicator, as a function of incremental changes in probe position along the slotted section, are recorded and plotted. The measurement is repeated for the probe traveling in the opposite direction.

c. If any appreciable difference exists in the data plotted for both directions of probe travel, an attempt should be made to correlate the information with structural defects and misalignment.

Exercises (665):

1. In using a waveguide slotted line, to what item in the

operation should the technician pay particular attention in order to preclude error in measurement?

2. Reflections due to change in impedance and discontinuities at the end of the slot in a slotted line may have significant effects on measurement accuracy. What part or parts of the slotted line's design make these errors smaller?

666. State the precautions necessary in the operation of slide screw tuners, and compare probe insertion loss and VSWR.

Slide-Screw Tuners. Waveguide slide-screw tuners are used primarily for correcting discontinuities or "flattening" the lines in waveguide systems. These tuners are also used to match loads, terminations, bolometer mounts, or antennas to the characteristic admittance of the waveguide. Slide-screw tuners are particularly valuable in determining experimentally the position and magnitude of matching structures required in waveguide systems.

The HP–X870A slide-screw tuner is the one with which you are mainly concerned. This tuner consists of a waveguide slotted section with a precision-built carriage on which is mounted an adjustable probe. The position and penetration of the probe is adjusted to set up a reflection, which is used to cancel out an existing reflection in a system. Probe penetration into the guide is varied by a micrometer drive on the HP–X870A. Position of the probe along the guide is adjusted by a thumb-operated wheel, and position is read to 0.1 millimeter on a vernier scale. The maximum VSWR of 20 can be corrected with an accuracy of 1.02, and small VSWRs can be exactly corrected. The HP–X870A is recommended for use at a VSWR up to 20. At this ratio, the insertion loss is approximately 2 dB. The insertion loss decreases approximately in proportion to the decrease in VSWR. (NOTE: Since the micrometer is set to read zero with the probe at full penetration—the reading at zero penetration being equal to the height of the waveguide—the micrometer should never be forced beyond zero, or the tuner may be damaged.)

Exercises (666):

1. What precaution should always be observed when you are using the HP–X870A slide-screw tuner?

2. What is the relationship between probe insertion loss and VSWR?

667. Identify the hazards associated with microwave radiation, and state the precautions to be taken to avoid them.

Microwave Radiation Hazards. In concluding this chapter, it seems appropriate that we recall some of the hazards inherent in microwave radiation. Since microwave radiation is potentially dangerous to the technician, we will discuss the hazards commonly encountered and the precautions necessary for the safety of those technicians concerned.

Hazards. Although the power levels of microwave energy with which you will be concerned are low, a potential danger still exists. Even low RF power levels can cause serious eye damage under the right conditions. For example, you will risk such damage if you look directly into any operating microwave source, such as a section of waveguide connected to an operating system. The nature of RF energy is such that internal burns or tissue and bone damage may result without your knowing it. What feels like a mildly warm sensation may be an indication of the presence of high intensity RF radiation with its accompanying hazardous effects. The brain, nerve cells, and reproductive organs are particularly susceptible to damage from RF radiation.

Precautions. The potential danger of microwave radiation dictates observation of the following safety precautions by all personnel.

a. Avoid looking directly into microwave sources (antennas, open waveguides, etc.) when power is applied to the system.

b. Avoid standing in any microwave beam for an appreciable length of time.

c. If any body heating effects are noted from a microwave beam, immediately move away from the beam source.

d. Allow only authorized personnel into the vicinity of potential exposure to microwave radiation.

Since radiation cannot be seen, the PME technicians must rely upon their knowledge of the effects of radiation to protect themselves and others from the dangers thereof.

Exercises (667):

1. Why should power be removed from a microwave system before inspecting waveguide components for damage?

2. Which organs and cells of the body are most susceptible to damage from RF radiation?

3. What physical indication may be present in the vicinity of RF radiation?

4. What should you do to avoid damage to body tissue from microwave radiation?

668. State the purpose and facts about operation of the HP–423A Crystal Detector.

Description. The Hewlett–Packard Model 423A and 8470A Crystal Detectors are 50-ohm (nominal) devices designed for measurement use in coaxial systems. The instruments convert RF power levels applied to the 50-ohm input connector into proportional values of dc voltage. The instruments measure relative power up to 100 mW and have a BNC female connector for the output jack which allows the detected output to be connected to a SWR meter. The output voltage polarity is negative, unless Option 003 is selected. The frequency range of the 423A is 10 MHz to 12.4 GHz. The 8470A's frequency range extends from 10 MHz to 18 GHz.

Operating Precautions. Static discharge can damage the detector element. A 100 pF capacitor (equivalent to 1.2 meters of coax cable) charged to 14 volts stores 0.1 erg, the maximum pulse rating of the detector element. Connect cables to test equipment and discharge the center conductor before connecting to the detector.

Do Not Needlessly Handle the Detector Element Used in the Crystal Detector. Static electricity which builds up on a person, especially on a cold dry day, must never be allowed to discharge through the crystal detector. Avoid exposed leads to or from the crystal detector, since these are often touched accidentally.

Operating Information. The crystal detector can be used as a demodulator to obtain a pulse envelope which can then be observed on an oscilloscope. It can also be used as a general purpose detector.

When using the crystal detector with an oscilloscope, and the waveshapes to be observed have rise times of less than 5 μs, the coaxial cable connecting oscilloscope and detector should be as short as possible and shunted with a resistor. Ideally, this resistor should be 50 ohms to terminate the coaxial cable properly. However, with 50 ohms of resistance, the output video pulse may be too small to drive some oscilloscopes. Therefore, the cable should be shunted with the smallest value of resistance that will obtain suitable deflection on the oscilloscope; typically the value will lie between 50Ω and 2 kΩ. The larger the resistance the more degradation of rise time.

The power applied to the detector can be either modulated or continuous wave (CW). If modulated at a 1000-Hz rate, an SWR meter can be used as an indicator. For CW detection, a dc milliammeter or millivoltmeter can be used as the indicator.

Exercises (668):

1. What is the purpose of the HP 423A Crystal Detector?

2. What is the polarity of the output voltage of the 423A Crystal Detector?

APPENDIXES

Appendix A. Table of Common Logarithms

Appendix B. Natural Sines, Cosines, and Tangents

APPENDIX A

TABLE OF COMMON LOGARITHMS

THE COMMON OR BRIGGS

LOGARITHMS

OF THE NATURAL NUMBERS

FROM 1 TO 1000

1–100

No.	Log.	No.	Log.	No.	Log.	No.	Log.	No	Log.
0		**20**	1. 30 103	**40**	1. 60 206	**60**	1. 77 815	**80**	1. 90 309
1	0. 00 000	21	1. 32 222	41	1. 61 278	61	1. 78 533	81	1. 90 849
2	0. 30 103	22	1. 34 242	42	1. 62 325	62	1. 79 239	82	1. 91 381
3	0. 47 712	23	1. 36 173	43	1. 63 347	63	1. 79 934	83	1. 91 908
4	0. 60 206	24	1. 38 021	44	1. 64 345	64	1. 80 618	84	1. 92 428
5	0. 69 897	25	1. 39 794	45	1. 65 321	65	1. 81 291	85	1. 92 942
6	0. 77 815	26	1. 41 497	46	1. 66 276	66	1. 81 954	86	1. 93 450
7	0.84 510	27	1. 43 136	47	1. 67 210	67	1. 82 607	87	1. 93 952
8	0.90 309	28	1. 44 716	48	1. 68 124	68	1. 83 251	88	1. 94 448
9	0.95 424	29	1. 46 240	49	1. 69 020	69	1. 83 885	89	1. 94 939
10	1. 00 000	**30**	1. 47 712	**50**	1. 69 897	**70**	1. 84 510	**90**	1. 95 424
11	1. 04 139	31	1. 49 136	51	1. 70 757	71	1. 85 126	91	1. 95 904
12	1. 07 918	32	1. 50 515	52	1. 71 600	72	1. 85 733	92	1. 96 379
13	1. 11 394	33	1. 51 851	53	1. 72 428	73	1. 86 332	93	1. 96 848
14	1. 14 613	34	1. 53 148	54	1. 73 239	74	1. 86 923	94	1. 97 313
15	1. 17 609	35	1. 54 407	55	1. 74 036	75	1. 87 506	95	1. 97 772
16	1. 20 412	36	1. 55 630	56	1. 74 819	76	1. 88 081	96	1. 98 227
17	1. 23 045	37	1. 56 820	57	1. 75 587	77	1. 88 64	97	1. 98 677
18	1. 25 527	38	1. 57 978	58	1. 76 343	78	1. 89 209	98	1. 99 123
19	1. 27 875	39	1. 59 106	59	1. 77 085	79	1. 89 763	99	1. 99 564
20	1. 30 103	**40**	1. 60 206	**60**	1. 77 815	**80**	1. 90 309	**100**	2. 00 000

No.	0	1	2	3	4	5	6	7	8	9
100	00 000	00 043	00 087	00 173	00 130	00 217	00 260	00 303	00 346	00 389
101	00 432	00 475	00 518	00 604	00 561	00 647	00 689	00 732	00 775	00 817
102	00 860	00 903	00 945	01 030	00 988	01 072	01 115	01 157	01 199	01 242
103	01 284	01 326	01 368	01 452	01 410	01 494	01 536	01 578	01 620	01 662
104	01 703	01 745	01 787	01 870	01 828	01 912	01 953	01 995	02 036	02 078
105	02 119	02 160	02 202	02 243	02 284	02 325	02 366	02 407	02 449	02 490
106	02 531	02 572	02 612	02 653	02 694	02 735	02 776	02 816	02 857	02 898
107	02 938	02 979	03 019	03 060	03 100	03 141	03 181	03 222	03 262	03 302
108	03 342	03 383	03 423	03 463	03 503	03 543	03 583	03 623	03 663	03 703
109	03 743	03 782	03 822	03 862	03 902	03 941	03 981	04 021	04 060	04 100
110	04 139	04 179	04 218	04 258	04 297	04 336	04 376	04 415	04 454	04 493
111	04 532	04 571	04 610	04 650	04 689	04 727	04 766	04 805	04 844	04 883
112	04 922	04 961	04 999	05 038	05 077	05 115	05 154	05 192	05 231	05 269
113	05 308	05 346	05 385	05 423	05 461	05 500	05 538	05 576	05 614	05 652
114	05 690	05 729	05 767	05 805	05 843	05 881	05 918	05 956	05 994	06 032
115	06 070	06 108	06 145	06 183	06 221	06 258	06 296	06 333	06 371	06 408
116	06 446	06 483	06 521	06 558	06 595	06 633	06 670	06 707	06 744	06 781
117	06 819	06 856	06 893	06 930	06 967	07 004	07 041	07 078	07 115	07 151
118	07 188	07 225	07 262	07 298	07 335	07 372	07 408	07 445	07 482	07 518
119	07 555	07 591	07 628	07 664	07 700	07 737	07 773	07 809	07 846	07 882
120	07 918	07 954	07 990	08 027	08 063	08 099	08 135	08 171	08 207	08 243
121	08 279	08 314	08 350	08 386	08 422	08 458	08 493	08 529	08 565	08 600
122	08 636	08 672	08 707	08 743	08 778	08 814	08 849	08 884	08 920	08 955
123	08 991	09 026	09 061	09 096	09 132	09 167	09 202	09 237	09 272	09 307
124	09 342	09 377	09 412	09 447	09 482	09 517	09 552	09 587	09 621	09 656
125	09 691	09 726	09 760	09 795	09 830	09 864	09 899	09 934	09 968	10 003
126	10 037	10 072	10 106	10 140	10 175	10 209	10 243	10 278	10 312	10 346
127	10 380	10 415	10 449	10 483	10 517	10 551	10 585	10 619	10 653	10 687
128	10 721	10 755	10 789	10 823	10 857	10 890	10 924	10 958	10 992	11 025
129	11 059	11 093	11 126	11 160	11 193	11 227	11 261	11 294	11 327	11 361
130	11 394	11 428	11 461	11 494	11 528	11 561	11 594	11 628	11 661	11 694
131	11 727	11 760	11 793	11 826	11 860	11 893	11 926	11 959	11 992	12 024
132	12 057	12 090	12 123	12 156	12 189	12 222	12 254	12 287	12 320	12 352
133	12 385	12 418	12 450	12 483	12 516	12 548	12 581	12 613	12 646	12 678
134	12 710	12 743	12 775	12 808	12 840	12 872	12 905	12 937	12 969	13 001
135	13 033	13 066	13 098	13 130	13 162	13 194	13 226	13 258	13 290	13 322
136	13 354	13 386	13 418	13 450	13 481	13 513	13 545	13 577	13 609	13 640
137	13 672	13 704	13 735	13 767	13 799	13 830	13 862	13 893	13 925	13 956
138	13 988	14 019	14 051	14 082	14 114	14 145	14 176	14 208	14 239	14 270
139	14 301	14 333	14 364	14 395	14 426	14 457	14 489	14 520	14 551	14 582
140	14 613	14 644	14 675	14 706	14 737	14 768	14 799	14 829	14 860	14 891
141	14 922	14 953	14 983	15 014	15 045	15 076	15 106	15 137	15 168	15 198
142	15 229	15 259	15 290	15 320	15 351	15 381	15 412	15 442	15 473	15 503
143	15 534	15 564	15 594	15 625	15 655	15 685	15 715	15 746	15 776	15 806
144	15 836	15 866	15 897	15 927	15 957	15 987	16 017	16 047	16 077	16 107
145	16 137	16 167	16 197	16 227	16 256	16 286	16 316	16 346	16 376	16 406
146	16 435	16 465	16 495	16 524	16 554	16 584	16 613	16 643	16 673	16 702
147	16 732	16 761	16 791	16 820	16 850	16 879	16 909	16 938	16 967	16 997
148	17 026	17 056	17 085	17 114	17 143	17 173	17 202	17 2 1	17 260	17 289
149	17 319	17 348	17 377	17 406	17 435	17 464	17 493	17 522	17 551	17 580
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
150	17 609	17 638	17 667	17 696	17 725	17 754	17 782	17 811	17 840	17 869
151	17 898	17 926	17 955	17 984	18 013	18 0 1	18 070	18 099	18 127	18 156
152	18 184	18 213	18 241	18 270	18 298	18 327	18 355	18 384	18 412	18 441
153	18 469	18 498	18 526	18 554	18 583	18 611	18 639	18 667	18 696	18 721
154	18 752	18 780	18 808	18 837	18 865	18 893	18 921	18 949	18 977	19 005
155	19 033	19 061	19 089	19 117	19 145	19 173	19 201	19 229	19 257	19 285
156	19 312	19 310	19 368	19 396	19 424	19 451	19 479	19 507	19 535	19 562
157	19 590	19 618	19 615	19 673	19 700	19 728	19 756	19 783	19 811	19 838
158	19 866	19 893	19 921	19 948	19 976	20 003	20 030	20 058	20 085	20 112
159	20 140	20 167	20 194	20 222	20 249	20 276	20 303	20 330	20 358	20 385
160	20 412	20 439	20 466	20 493	20 520	20 548	20 575	20 602	20 629	20 656
161	20 683	20 710	20 737	20 763	20 790	20 817	20 844	20 871	20 898	20 925
162	20 952	20 978	21 005	21 032	21 059	21 085	21 112	21 139	21 165	21 192
163	21 219	21 245	21 272	21 299	21 325	21 352	21 378	21 405	21 431	21 458
164	21 484	21 511	21 537	21 564	21 590	21 617	21 643	21 669	21 696	21 722
165	21 748	21 775	21 801	21 827	21 854	21 880	21 906	21 932	21 958	21 985
166	22 011	22 037	22 063	22 089	22 115	22 141	22 167	22 194	22 220	22 216
167	22 272	22 298	22 324	22 350	22 376	22 401	22 427	22 453	22 479	22 505
168	22 531	22 557	22 583	22 608	22 634	22 660	22 686	22 712	22 737	22 763
169	22 789	22 814	22 840	22 866	22 891	22 917	22 943	22 968	22 994	23 019
170	23 045	23 070	23 096	23 121	23 147	23 172	23 198	23 223	23 249	23 274
171	23 300	23 325	23 350	23 376	23 401	23 426	23 452	23 477	23 502	23 528
172	23 553	23 578	23 603	23 629	23 654	23 679	23 704	23 729	23 754	23 779
173	23 805	23 830	23 855	23 880	23 905	23 930	23 955	23 980	24 005	24 030
174	24 055	24 080	24 105	24 130	24 155	24 180	24 204	24 229	24 254	24 279
175	24 304	24 329	24 353	24 378	24 403	24 428	24 452	24 477	24 502	24 527
176	24 551	24 576	24 601	24 625	24 650	24 674	24 699	24 724	24 748	24 773
177	24 797	24 822	24 846	24 871	24 895	24 920	24 944	24 969	24 993	25 018
178	25 042	25 066	25 091	25 115	25 139	25 164	25 188	25 212	25 237	25 261
179	25 285	25 310	25 334	25 358	25 382	25 406	25 431	25 455	25 479	25 503
180	25 527	25 551	25 575	25 600	25 624	25 648	25 672	25 696	25 720	25 744
181	25 768	25 792	25 816	25 840	25 864	25 888	25 912	25 935	25 959	25 983
182	26 007	26 031	26 055	26 079	26 102	26 126	26 150	26 174	26 198	26 221
183	26 245	26 269	26 293	26 316	26 340	26 364	26 387	26 411	26 435	26 458
184	26 482	26 505	26 529	26 553	26 576	26 600	26 623	26 647	26 670	26 694
185	26 717	26 741	26 764	26 788	26 811	26 834	26 858	26 881	26 905	26 928
186	26 951	26 975	26 998	27 021	27 045	27 068	27 091	27 114	27 138	27 161
187	27 184	27 207	27 231	27 254	27 277	27 300	27 323	27 346	27 370	27 393
188	27 416	27 439	27 462	27 485	27 508	27 531	27 554	27 577	27 600	27 623
189	27 646	27 669	27 692	27 715	27 738	27 761	27 784	27 807	27 830	27 852
190	27 875	27 898	27 921	27 944	27 967	27 989	28 012	28 035	28 058	28 081
191	28 103	28 126	28 149	28 171	28 194	28 217	28 240	28 262	28 285	28 307
192	28 330	28 353	28 375	28 398	28 421	28 443	28 466	28 488	28 511	28 533
193	28 556	28 578	28 601	28 623	28 646	28 668	28 691	28 713	28 735	28 758
194	28 780	28 803	28 825	28 847	28 870	28 892	28 914	28 937	28 959	28 981
195	29 003	29 026	29 048	29 070	29 092	29 115	29 137	29 159	29 181	29 203
196	29 226	29 248	29 270	29 292	29 314	29 336	29 358	29 380	29 403	29 425
197	29 447	29 469	29 491	29 513	29 535	29 557	29 579	29 601	29 623	29 645
198	29 667	29 688	29 710	29 732	29 754	29 776	29 798	29 820	29 842	29 863
199	29 885	29 907	29 929	29 951	29 973	29 994	30 016	30 038	30 060	30 081
No.	0	1	2	3	4	5	6	7	8	9

No.	0	1	2	3	4	5	6	7	8	9
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201	30 320	30 311	30 363	30 384	30 406	30 428	30 449	30 471	30 492	30 514
202	30 535	30 557	30 578	30 600	30 621	30 613	30 664	30 685	30 707	30 728
203	30 750	30 771	30 792	30 814	30 835	30 856	30 878	30 899	30 920	30 942
204	30 963	30 984	31 006	31 027	31 048	31 069	31 091	31 112	31 133	31 154
205	31 175	31 197	31 218	31 239	31 260	31 281	31 302	31 323	31 345	31 366
206	31 387	31 408	31 429	31 450	31 471	31 492	31 513	31 534	31 555	31 576
207	31 597	31 618	31 639	31 660	31 681	31 702	31 723	31 744	31 765	31 785
208	31 806	31 827	31 848	31 869	31 890	31 911	31 931	31 952	31 973	31 994
209	32 015	32 035	32 056	32 077	32 098	32 118	32 139	32 160	32 181	32 201
210	32 222	32 243	32 263	32 284	32 305	32 325	32 346	32 366	32 387	32 408
211	32 428	32 449	32 469	32 490	32 510	32 531	32 552	32 572	32 593	32 613
212	32 634	32 654	32 675	32 695	32 715	32 736	32 756	32 777	32 797	32 818
213	32 838	32 858	32 879	32 899	32 919	32 910	32 960	32 980	33 001	33 021
214	33 041	33 062	33 082	33 102	33 122	33 143	33 163	33 183	33 203	33 224
215	33 244	33 264	33 284	33 304	33 325	33 345	33 365	33 385	33 405	33 425
216	33 445	33 465	33 486	33 506	33 526	33 546	33 566	33 586	33 606	33 626
217	33 616	33 666	33 686	33 706	33 726	33 746	33 766	33 786	33 806	33 826
218	33 846	33 866	33 885	33 905	33 925	33 945	33 965	33 985	34 005	34 025
219	34 044	34 064	34 084	34 104	34 124	34 143	34 163	34 183	34 203	34 223
220	34 242	34 262	34 282	34 301	34 321	34 341	34 361	34 380	34 400	34 420
221	34 439	34 459	34 479	34 498	34 518	34 537	34 557	34 577	34 596	34 616
222	34 635	34 655	34 674	34 694	34 713	34 733	34 753	34 772	34 792	34 811
223	34 830	34 850	34 869	34 889	34 908	34 928	34 947	34 967	34 986	35 005
224	35 025	35 044	35 064	35 083	35 102	35 122	35 141	35 160	35 180	35 199
225	35 218	35 238	35 257	35 276	35 295	35 315	35 334	35 353	35 372	35 392
226	35 411	35 430	35 449	35 468	35 488	35 507	35 526	35 545	35 564	35 583
227	35 603	35 622	35 641	35 660	35 679	35 698	35 717	35 736	35 755	35 774
228	35 793	35 813	35 832	35 851	35 870	35 889	35 908	35 927	35 946	35 965
229	35 984	36 003	36 021	36 040	36 059	36 078	36 097	36 116	36 135	36 154
230	36 173	36 192	36 211	36 229	36 248	36 267	36 286	36 305	36 324	36 342
231	36 361	36 380	36 399	36 418	36 436	36 455	36 474	36 493	36 511	36 530
232	36 549	36 568	36 586	36 605	36 624	36 642	36 661	36 680	36 698	36 717
233	36 736	36 754	36 773	36 791	36 810	36 829	36 847	36 866	36 884	36 903
234	36 922	36 940	36 959	36 977	36 996	37 014	37 033	37 051	37 070	37 088
235	37 107	37 125	37 144	37 162	37 181	37 199	37 218	37 236	37 254	37 273
236	37 291	37 310	37 328	37 346	37 365	37 383	37 401	37 420	37 438	37 457
237	37 475	37 493	37 511	37 530	37 548	37 566	37 585	37 603	37 621	37 639
238	37 658	37 676	37 694	37 712	37 731	37 749	37 767	37 785	37 803	37 822
239	37 840	37 858	37 876	37 894	37 912	37 931	37 949	37 967	37 985	38 003
240	38 021	38 039	38 057	38 075	38 093	38 112	38 130	38 148	38 166	38 184
241	38 202	38 220	38 238	38 256	38 274	38 292	38 310	38 328	38 346	38 364
242	38 382	38 399	38 417	38 435	38 453	38 471	38 489	38 507	38 525	38 543
243	38 561	38 578	38 596	38 614	38 632	38 650	38 668	38 686	38 703	38 721
244	38 739	38 757	38 775	38 792	38 810	38 828	38 846	38 863	38 881	38 899
245	38 917	38 934	38 952	38 970	38 987	39 005	39 023	39 041	39 058	39 076
246	39 094	39 111	39 129	39 146	39 164	39 182	39 199	39 217	39 235	39 252
247	39 270	39 287	39 305	39 322	39 340	39 358	39 375	39 393	39 410	39 428
248	39 445	39 463	39 480	39 498	39 515	39 533	39 550	39 568	39 585	39 602
249	39 620	39 637	39 655	39 672	39 690	39 707	39 724	39 742	39 759	39 777
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

200–249

No.	0	1	2	3	4	5	6	7	8	9
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251	39 967	39 985	40 002	40 019	40 037	40 034	40 071	40 088	40 106	40 123
252	40 140	40 157	40 175	40 192	40 209	40 220	40 243	40 261	40 278	40 295
253	40 312	40 329	40 346	40 364	40 381	40 398	40 415	40 432	40 449	40 466
254	40 483	40 500	40 518	40 535	40 552	40 569	40 586	40 603	40 620	40 637
255	40 654	40 671	40 688	40 705	40 722	40 739	40 756	40 773	40 790	40 807
256	40 824	40 811	40 858	40 875	40 892	40 909	40 926	40 943	40 960	40 976
257	40 993	41 010	41 027	41 0	41 061	41 078	41 095	41 111	41 128	41 145
258	41 162	41 179	41 196	41 212	41 229	41 246	41 263	41 280	41 296	41 313
259	41 330	41 3 7	41 363	41 380	41 397	41 414	41 430	41 447	41 464	41 481
260	41 497	41 514	41 531	41 547	41 564	41 581	41 597	41 614	41 631	41 617
261	41 664	41 681	41 697	41 714	41 731	41 747	41 764	41 780	41 797	41 814
262	41 830	41 817	41 863	41 880	41 896	41 913	41 929	41 946	41 963	41 979
263	41 996	42 012	42 029	42 015	42 062	42 078	42 095	42 111	42 127	42 144
264	42 160	42 177	42 193	42 210	42 226	42 213	42 259	42 275	42 292	42 308
265	42 25	42 341	42 357	42 374	42 390	42 406	42 423	42 439	42 455	42 472
266	42 488	42 504	42 521	42 537	42 553	42 570	42 586	42 602	42 619	42 635
267	42 651	42 667	42 684	42 700	42 716	42 732	42 749	42 765	42 781	42 797
268	42 813	42 830	42 8 6	42 862	42 878	42 894	42 911	42 927	42 943	42 959
269	42 975	42 991	43 008	43 024	43 010	43 056	43 072	43 088	43 104	43 120
270	43 136	43 152	43 169	43 185	43 201	43 217	43 233	43 249	43 265	43 281
271	43 297	43 313	43 329	43 345	43 361	43 377	43 393	43 409	43 425	43 441
272	43 457	43 473	43 489	43 505	43 521	43 537	43 553	43 569	43 584	43 600
273	43 616	43 632	43 648	43 664	43 680	43 696	43 712	43 727	43 743	43 759
274	43 775	43 791	43 807	43 823	43 838	43 854	43 870	43 886	43 902	43 917
275	43 933	43 949	43 965	43 981	43 996	44 013	44 028	44 044	44 059	44 075
276	44 091	44 107	44 122	44 138	44 154	44 170	44 185	44 201	44 217	44 232
277	44 218	44 264	44 279	44 296	44 311	44 326	44 312	44 358	44 373	44 389
278	44 404	44 420	44 436	44 451	44 467	44 483	44 498	44 514	44 529	44 545
279	44 560	44 576	44 592	44 607	44 623	44 638	44 654	44 669	44 685	44 700
280	44 716	44 731	44 747	44 762	44 778	44 793	44 809	44 824	44 840	44 855
281	44 871	44 886	44 902	44 917	44 932	44 918	44 963	44 979	44 994	45 010
282	45 025	45 040	45 056	45 071	45 086	45 102	45 117	45 133	45 148	45 163
283	45 179	45 194	45 209	45 225	45 240	45 255	45 271	45 286	45 301	45 317
284	45 332	45 347	45 362	45 378	45 393	45 408	45 423	45 439	45 454	45 469
285	45 484	45 500	45 515	45 530	45 545	45 561	45 576	45 591	45 606	45 621
286	45 637	45 652	45 667	45 682	45 697	45 712	45 728	45 743	45 758	45 773
287	45 788	45 803	45 818	45 834	45 849	45 864	45 879	45 894	45 909	45 924
288	45 939	45 954	45 969	45 984	46 000	46 015	46 030	46 045	46 060	46 075
289	46 090	46 105	46 120	46 135	46 150	46 165	46 180	46 195	46 210	46 225
290	46 240	46 255	46 270	46 285	46 300	46 315	46 330	46 345	46 359	46 374
291	46 389	46 404	46 419	46 4 4	46 449	46 464	46 479	46 494	46 509	46 523
292	46 538	46 553	46 568	46 583	46 598	46 613	46 627	46 642	46 657	46 672
293	46 687	46 702	46 716	46 731	46 746	46 761	46 776	46 790	46 805	46 820
294	46 835	46 850	46 864	46 879	46 894	46 909	46 923	46 938	46 953	46 967
295	46 982	46 997	47 012	47 026	47 041	47 056	47 070	47 085	47 100	47 114
296	47 129	47 144	47 159	47 173	47 188	47 202	47 217	47 232	47 246	47 261
297	47 276	47 290	47 305	47 319	47 334	47 349	47 363	47 378	47 392	47 407
298	47 422	47 436	47 451	47 465	47 480	47 494	47 509	47 524	47 538	47 553
299	47 567	47 582	47 596	47 611	47 625	47 640	47 654	47 669	47 683	47 698
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
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301	47 857	47 871	47 885	47 900	47 914	47 929	47 913	47 958	47 972	47 986
302	48 001	48 015	48 029	48 044	48 058	48 073	48 087	48 101	48 116	48 130
303	48 144	48 159	48 173	48 187	48 202	48 216	48 230	48 244	48 259	48 273
304	48 287	48 302	48 316	48 330	48 344	48 359	48 373	48 387	48 401	48 416
305	48 430	48 444	48 458	48 473	48 487	48 501	48 515	48 530	48 544	48 558
306	48 572	48 586	48 601	48 615	48 629	48 643	48 657	48 671	48 686	48 700
307	48 714	48 728	48 742	48 756	48 770	48 785	48 799	48 813	48 827	48 811
308	48 855	48 869	48 883	48 897	48 911	48 926	48 910	48 954	48 968	48 982
309	48 996	49 010	49 024	49 038	49 052	49 066	49 080	49 094	49 108	49 122
310	49 136	49 150	49 164	49 178	49 192	49 206	49 220	49 234	49 248	49 262
311	49 276	49 290	49 304	49 318	49 332	49 316	49 360	49 374	49 388	49 402
312	49 415	49 429	49 443	49 457	49 471	49 485	49 499	49 513	49 527	49 511
313	49 554	49 568	49 582	49 596	49 610	49 624	49 638	49 651	49 665	49 679
314	49 693	49 707	49 721	49 734	49 748	49 762	49 776	49 790	49 803	49 817
315	49 831	49 845	49 859	49 872	49 886	49 900	49 914	49 927	49 941	49 955
316	49 969	49 982	49 996	50 010	50 024	50 037	50 051	50 065	50 079	50 092
317	50 106	50 120	50 133	50 147	50 161	50 174	50 188	50 202	50 215	50 229
318	50 243	50 256	50 270	50 284	50 297	50 311	50 325	50 338	50 352	50 365
319	50 379	50 393	50 406	50 420	50 433	50 447	50 461	50 474	50 488	50 501
320	50 515	50 529	50 542	50 556	50 569	50 583	50 596	50 610	50 623	50 637
321	50 651	50 664	50 678	50 691	50 705	50 718	50 732	50 745	50 759	50 772
322	50 786	50 799	50 813	50 826	50 840	50 853	50 866	50 880	50 893	50 907
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324	51 055	51 068	51 081	51 095	51 108	51 121	51 135	51 148	51 162	51 175
325	51 188	51 202	51 215	51 228	51 242	51 255	51 268	51 282	51 295	51 308
326	51 322	51 335	51 348	51 362	51 375	51 388	51 402	51 415	51 428	51 441
327	51 455	51 468	51 481	51 495	51 508	51 521	51 534	51 548	51 561	51 574
328	51 587	51 601	51 614	51 627	51 640	51 654	51 667	51 680	51 693	51 706
329	51 720	51 733	51 746	51 759	51 772	51 786	51 799	51 812	51 825	51 838
330	51 851	51 865	51 878	51 891	51 904	51 917	51 930	51 943	51 957	51 970
331	51 983	51 996	52 009	52 022	52 035	52 048	52 061	52 075	52 088	52 101
332	52 114	52 127	52 140	52 153	52 166	52 179	52 192	52 205	52 218	52 231
333	52 244	52 257	52 270	52 284	52 297	52 310	52 323	52 336	52 349	52 362
334	52 375	52 388	52 401	52 414	52 427	52 440	52 453	52 466	52 479	52 492
335	52 504	52 517	52 530	52 543	52 556	52 569	52 582	52 595	52 608	52 621
336	53 634	52 647	52 660	52 673	52 686	52 699	52 711	52 724	52 737	52 750
337	52 763	52 776	52 789	52 802	52 815	52 827	52 840	52 853	52 866	52 879
338	52 892	52 905	52 917	52 930	52 943	52 956	52 969	52 982	52 994	53 007
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341	53 275	53 288	53 301	53 314	53 326	53 339	53 352	53 364	53 377	53 390
342	53 403	53 415	53 428	53 441	53 453	53 466	53 479	53 491	53 504	53 517
343	53 529	53 542	53 555	53 567	53 580	53 593	53 605	53 618	53 631	53 613
344	53 656	53 668	53 681	53 694	53 706	53 719	53 732	53 744	53 757	53 769
345	53 782	53 794	53 807	53 820	53 832	53 845	53 857	53 870	53 882	53 895
346	53 908	53 920	53 933	53 945	53 958	53 970	53 983	53 995	54 008	54 020
347	54 033	54 045	54 058	54 070	54 083	54 095	54 108	54 120	54 133	54 145
348	54 158	54 170	54 183	54 195	54 208	54 220	54 233	54 245	54 258	54 270
349	54 283	54 295	54 307	54 320	54 332	54 345	54 357	54 370	54 382	54 394
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
350	54 407	54 419	54 432	54 444	54 456	54 469	54 481	54 494	54 506	54 518
351	54 531	54 543	54 555	54 568	54 580	54 593	54 605	54 617	54 630	54 612
352	54 654	54 667	54 679	54 691	54 704	54 716	54 728	54 741	54 753	54 765
353	54 777	54 790	54 802	54 814	54 827	54 839	54 851	54 864	54 876	54 888
354	54 900	54 913	54 925	54 937	54 949	54 962	54 974	54 986	54 998	55 011
355	55 023	55 035	55 0 7	55 060	55 072	55 084	55 096	55 108	55 121	55 133
356	55 145	55 157	55 169	55 182	55 194	55 206	55 218	55 230	55 242	55 255
357	55 267	55 279	55 291	55 303	55 315	55 328	55 340	55 352	55 364	55 376
358	55 388	55 400	55 413	55 425	55 437	55 449	55 461	55 473	55 485	55 497
359	55 509	55 522	55 534	55 546	55 558	55 570	55 582	55 594	55 606	55 618
360	55 630	55 642	55 654	55 666	55 678	55 691	55 703	55 715	55 727	55 739
361	55 751	55 763	55 775	55 787	55 799	55 811	55 823	55 835	55 847	55 859
362	55 871	55 883	55 895	55 907	55 919	55 931	55 943	55 955	55 967	55 979
363	55 991	56 003	56 015	56 027	56 038	56 050	56 062	56 074	56 086	56 098
364	56 110	56 122	56 134	56 146	56 158	56 170	56 182	56 194	56 205	56 217
365	56 229	56 241	56 253	56 265	56 277	56 289	56 301	56 312	56 324	56 336
366	56 348	56 360	56 372	56 384	56 396	56 407	56 419	56 431	56 443	56 455
367	56 467	56 478	56 490	56 502	56 514	56 526	56 538	56 549	56 561	56 573
368	56 585	56 597	56 608	56 620	56 632	56 644	56 656	56 667	56 679	56 691
369	56 703	56 714	56 726	56 738	56 750	56 761	56 773	56 785	56 797	56 808
370	56 820	56 832	56 844	56 855	56 867	56 879	56 891	56 902	56 914	56 926
371	56 937	56 949	56 961	56 972	56 984	56 996	57 008	57 019	57 031	57 043
372	57 054	57 066	57 078	57 089	57 101	57 113	57 124	57 136	57 148	57 159
373	57 171	57 183	57 194	57 206	57 217	57 229	57 241	57 252	57 264	57 276
374	57 287	57 299	57 310	57 322	57 334	57 345	57 357	57 368	57 380	57 392
375	57 403	57 415	57 426	57 438	57 449	57 461	57 473	57 484	57 496	57 507
376	57 519	57 530	57 542	57 553	57 565	57 576	57 588	57 600	57 611	57 623
377	57 634	57 646	57 657	57 669	57 680	57 692	57 703	57 715	57 726	57 738
378	57 749	57 761	57 772	57 784	57 795	57 807	5/ 818	57 830	57 841	57 852
379	57 864	57 875	57 887	57 898	57 910	57 921	57 933	57 944	57 955	57 967
380	57 978	57 990	58 001	58 013	58 024	58 035	58 047	58 058	58 070	58 081
381	58 092	58 104	58 115	58 127	58 138	58 149	58 161	58 172	58 184	58 195
382	58 206	58 218	58 229	58 240	58 252	58 263	58 274	58 286	58 297	58 309
383	58 320	58 331	58 343	58 354	58 365	58 377	58 388	58 399	58 410	58 422
384	58 433	58 444	58 456	58 467	58 478	58 490	58 501	58 512	58 524	58 535
385	58 546	58 557	58 569	58 580	58 591	58 602	58 614	58 625	58 636	58 647
386	58 659	58 670	58 681	58 692	58 704	58 715	58 726	58 737	58 749	58 760
387	58 771	58 782	58 794	58 805	58 816	58 827	58 838	58 850	58 861	58 872
388	58 883	58 894	58 906	58 917	58 928	58 939	58 950	58 961	58 973	58 984
389	58 995	59 006	59 017	59 028	59 040	59 051	59 062	59 073	59 084	59 095
390	59 106	59 118	59 129	59 140	59 151	59 162	59 173	59 184	59 195	59 207
391	59 218	59 229	59 240	59 251	59 262	59 273	59 284	59 295	59 306	59 318
392	59 329	59 340	59 351	59 362	59 373	59 384	59 395	59 406	59 417	59 428
393	59 439	59 450	59 461	59 472	59 483	59 494	59 506	59 517	59 528	59 539
394	59 550	59 561	59 572	59 583	59 594	59 605	59 616	59 627	59 638	59 649
395	59 660	59 671	59 682	59 693	59 704	59 715	59 726	59 737	59 748	59 759
396	59 770	59 780	59 791	59 802	59 813	59 824	59 835	59 846	59 857	59 868
397	59 879	59 890	59 901	59 912	59 923	59 934	59 945	59 956	59 966	59 977
398	59 988	59 999	60 010	60 021	60 032	60 043	60 054	60 065	60 076	60 086
399	60 097	60 108	60 119	60 130	60 141	60 152	60 163	60 173	60 184	60 195
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
400	60 206	60 217	60 228	60 239	60 249	60 260	60 271	60 282	60 293	60 301
401	60 314	60 325	60 336	60 317	60 358	60 369	60 379	60 390	60 401	60 412
402	60 423	60 433	60 444	60 455	60 466	60 477	60 487	60 498	60 509	60 520
403	60 531	60 541	60 552	60 563	60 571	60 581	60 595	60 606	60 617	60 627
404	60 638	60 649	60 660	60 670	60 681	60 692	60 703	60 713	60 724	60 735
405	60 746	60 756	60 767	60 778	60 788	60 799	60 810	60 821	60 831	60 842
406	60 853	60 863	60 874	60 885	60 895	60 906	60 917	60 927	60 938	60 919
407	60 959	60 970	60 981	60 991	61 002	61 013	61 023	61 031	61 015	61 055
408	61 066	61 077	61 087	61 098	61 109	61 119	61 130	61 110	61 151	61 162
409	61 172	61 183	61 194	61 204	61 215	61 225	61 236	61 247	61 257	61 268
410	61 278	61 289	61 300	61 310	61 321	61 331	61 342	61 352	61 363	61 374
411	61 384	61 395	61 405	61 416	61 426	61 437	61 448	61 458	61 469	61 479
412	61 490	61 500	61 511	61 521	61 532	61 542	61 553	61 563	61 574	61 584
413	61 595	61 606	61 616	61 627	61 637	61 648	61 658	61 669	61 679	61 690
414	61 700	61 711	61 721	61 731	61 742	61 752	61 763	61 773	61 784	61 794
415	61 805	61 815	61 826	61 836	61 847	61 857	61 868	61 878	61 888	61 899
416	61 909	61 920	61 930	61 941	61 951	61 962	61 972	61 982	61 993	62 003
417	62 014	62 024	62 034	62 045	62 055	62 066	62 076	62 086	62 097	62 107
418	62 118	62 128	62 138	62 149	62 159	62 170	62 180	62 190	62 201	62 211
419	62 221	62 232	62 242	62 252	62 263	62 273	62 284	62 294	62 304	62 315
420	62 325	62 335	62 346	62 356	62 366	62 377	62 387	62 397	62 408	62 418
421	62 428	62 439	62 449	62 459	62 469	62 480	62 490	62 500	62 511	62 521
422	62 531	62 542	62 552	62 562	62 572	62 583	62 593	62 603	62 613	62 624
423	62 634	62 644	62 655	62 665	62 675	62 685	62 696	62 706	62 716	62 726
424	62 737	62 747	62 757	62 767	62 778	62 788	62 798	62 808	62 818	62 829
425	62 839	62 849	62 859	62 870	62 880	62 890	62 900	62 910	62 921	62 931
426	62 941	62 951	62 961	62 972	62 982	62 992	63 002	63 012	63 022	63 033
427	63 043	63 053	63 063	63 073	63 083	63 094	63 104	63 114	63 124	63 134
428	63 144	63 155	63 165	63 175	63 185	63 195	63 205	63 215	63 225	63 236
429	63 246	63 256	63 266	63 276	63 286	63 296	63 306	63 317	63 327	63 337
430	63 347	63 357	63 367	63 377	63 387	63 397	63 407	63 417	63 428	63 438
431	63 448	63 458	63 468	63 478	63 488	63 498	63 508	63 518	63 528	63 538
432	63 548	63 558	63 568	63 579	63 589	63 599	63 609	63 619	63 629	63 639
433	63 649	63 659	63 669	63 679	63 689	63 699	63 709	63 719	63 729	63 739
434	63 749	63 759	63 769	63 779	63 789	63 799	63 809	63 819	63 829	63 839
435	63 849	63 859	63 869	64 375	63 889	63 899	63 909	63 919	63 929	63 939
436	63 949	63 959	63 969	64 473	63 988	63 998	64 008	64 018	64 028	64 038
437	64 048	64 058	64 068	64 572	64 088	64 098	64 108	64 118	64 128	64 137
438	64 147	64 157	64 167	64 670	64 187	64 197	64 207	64 217	64 227	64 237
439	64 246	64 256	64 266	64 768	64 286	64 296	64 306	64 316	64 326	64 335
440	64 345	64 355	64 365	64 865	64 385	64 395	64 404	64 414	64 424	64 434
441	64 444	64 454	64 464	64 963	64 483	64 493	64 503	64 513	64 523	64 532
442	64 542	64 552	64 562	65 060	64 582	64 591	64 601	64 611	64 621	64 631
443	64 640	64 650	64 660	65 157	64 680	64 689	64 699	64 709	64 719	64 729
444	64 738	64 748	64 758	65 254	64 777	64 787	64 797	64 807	64 816	64 826
445	64 836	64 846	64 856	63 879	64 875	64 885	64 895	64 904	64 914	64 924
446	64 933	64 943	64 953	63 979	64 972	64 982	64 992	65 002	65 011	65 021
447	65 031	65 040	65 050	64 078	65 070	65 079	64 089	65 099	65 108	65 118
448	65 128	65 137	65 147	64 177	65 167	65 176	65 186	65 196	65 205	65 215
449	65 225	65 234	65 244	64 276	65 263	65 273	65 283	65 292	65 302	65 312
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
450	65 321	65 331	65 341	65 35	65 360	65 369	65 379	65 389	65 398	65 408
451	65 418	65 427	65 437	65 447	65 456	65 466	65 475	65 485	65 495	65 504
452	65 514	65 523	65 533	65 543	65 552	65 562	65 571	65 581	65 591	65 600
453	65 610	65 619	65 629	65 639	65 648	65 658	65 667	65 677	65 686	65 696
454	65 706	65 715	65 725	65 734	65 744	65 753	65 763	65 772	65 782	65 792
455	65 801	65 811	65 820	65 830	65 839	65 849	65 858	65 868	65 877	65 887
456	65 896	65 906	65 916	65 925	65 935	65 944	65 954	65 963	65 973	65 982
457	65 992	66 001	66 011	66 020	66 030	66 039	66 049	66 058	66 068	66 077
458	66 087	66 096	66 106	66 115	66 124	66 134	66 143	66 153	66 162	66 172
459	66 181	66 191	66 200	66 210	66 219	66 229	66 238	66 247	66 257	66 266
460	66 276	66 285	66 295	66 304	66 314	66 323	66 332	66 342	66 351	66 361
461	66 370	66 380	66 389	66 398	66 408	66 417	66 427	66 436	66 445	66 455
462	66 464	66 474	66 483	66 492	66 502	66 511	66 521	66 530	66 539	66 549
463	66 558	66 567	66 577	66 586	66 596	66 605	66 614	66 624	66 633	66 642
464	66 652	66 661	66 671	66 680	66 689	66 699	66 708	66 717	66 727	66 736
465	66 745	66 755	66 764	66 773	66 783	66 792	66 801	66 811	66 820	66 829
466	66 839	66 848	66 857	66 867	66 876	66 885	66 894	66 904	66 913	66 922
467	66 932	66 941	66 950	66 960	66 969	66 978	66 987	66 997	67 006	67 015
468	67 025	67 034	67 043	67 052	67 062	67 071	67 080	67 089	67 099	67 108
469	67 117	67 127	67 136	67 145	67 154	67 164	67 173	67 182	67 191	67 201
470	67 210	67 219	67 228	67 237	67 247	67 256	67 265	67 274	67 284	67 293
471	67 302	67 311	67 321	67 330	67 339	67 348	67 357	67 367	67 376	67 385
472	67 394	67 403	67 413	67 422	67 431	67 440	67 449	67 459	67 468	67 477
473	67 486	67 495	67 504	67 514	67 523	67 532	67 541	67 550	67 560	67 569
474	67 578	67 587	67 596	67 605	67 614	67624	67 633	67 642	67 651	67 660
475	67 669	67 679	67 688	67 697	67 706	67 715	67 724	67 733	67 742	67 752
476	67 761	67 770	67 779	67 788	67 797	67 806	67 815	67 825	67 834	67 843
477	67 852	67 861	67 870	67 879	67 888	67 897	67 906	67 916	67 925	67 934
478	67 943	67 952	67 961	67 970	67 979	67 988	67 997	68 006	68 015	68 024
479	68 034	68 043	68 052	68 061	68 070	68 079	68 088	68 097	68 106	68 115
480	68 124	68 133	68 142	68 151	68 160	68 169	68 178	68 187	68 196	68 205
481	68 215	68 224	68 233	68 242	68 251	68 260	68 269	68 278	68 287	68 296
482	68 305	68 314	68 323	68 332	68 341	68 350	68 359	68 368	68 377	68 386
483	68 395	68 404	68 413	68 422	68 431	68 440	68 449	68 458	68 467	68 476
484	68 485	68 494	68 502	68 511	68 520	68 529	68 538	68 547	68 556	68 565
485	68 574	68 583	68 592	68 601	68 610	68 619	68 628	68 637	68 646	68 655
486	68 664	68 673	68 681	68 690	68 699	68 708	68 717	68 726	68 735	68 744
487	68 753	68 762	68 771	68 780	68 789	68 797	68 806	68 815	68 824	68 833
488	68 842	68 851	68 860	68 869	68 878	68 886	68 895	68 904	68 913	68 922
489	68 931	68 940	68 949	68 958	68 966	68 975	68 984	68 993	69 002	69 011
490	69 020	69 028	69 037	69 046	69 055	69 064	69 073	69 082	69 090	69 099
491	69 108	69 117	69 126	69 135	69 144	69 152	69 161	69 170	69 179	69 188
492	69 197	69 205	69 214	69 223	69 232	69 241	69 249	69 258	69 267	69 276
493	69 285	69 294	69 302	69 311	69 320	69 329	69 338	69 346	69 355	69 364
494	69 373	69 381	69 390	69 399	69 408	69 417	69 425	69 434	69 443	69 452
495	69 461	69 469	69 478	69 487	69 496	69 504	69 513	69 522	69 531	69 539
496	69 548	69 557	69 566	69 574	69 583	69 592	69 601	69 609	69 618	69 627
497	69 636	69 644	69 653	69 662	69 671	69 679	69 688	69 697	69 705	69 714
498	69 723	69 732	69 740	69 749	69 758	69 767	69 775	69 784	69 793	69 801
499	69 810	69 819	69 827	69 836	69 845	69 854	69 862	69 871	69 880	69 888
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
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501	69 984	69 992	70 001	70 010	70 018	70 027	70 036	70 044	70 053	70 062
502	70 070	70 079	70 088	70 096	70 105	70 114	70 122	70 131	70 140	70 148
503	70 157	70 165	70 174	70 183	70 191	70 200	70 209	70 217	70 226	70 234
504	70 243	70 252	70 260	70 269	70 278	70 286	70 295	70 303	70 312	70 321
505	70 329	70 338	70 346	70 355	70 364	70 372	70 381	70 389	70 398	70 406
506	70 415	70 424	70 432	70 441	70 449	70 458	70 467	70 475	70 484	70 492
507	70 501	70 509	70 518	70 526	70 535	70 544	70 552	70 561	70 569	70 578
508	70 586	70 595	70 603	70 612	70 621	70 629	70 638	70 646	70 655	70 663
509	70 672	70 680	70 689	70 697	70 706	70 714	70 723	70 731	70 740	70 749
510	70 757	70 766	70 774	70 783	70 791	70 800	70 808	70 817	70 825	70 834
511	70 812	70 851	70 859	70 868	70 876	70 885	70 893	70 902	70 910	70 919
512	70 927	70 935	70 944	70 952	70 961	70 969	70 978	70 966	70 995	71 003
513	71 012	71 020	71 029	71 037	71 046	71 054	71 063	71 071	71 079	71 088
514	71 096	71 105	71 113	71 122	71 130	71 139	71 147	71 155	71 64	71 172
515	71 181	71 189	71 198	71 206	71 214	71 223	71 231	71 240	71 248	71 257
516	71 265	71 273	71 282	71 290	71 299	71 307	71 315	71 324	71 332	71 341
517	71 349	71 357	71 366	71 374	71 383	71391	71 399	71 408	71 416	71 425
518	71 433	71 441	71 450	71 458	71 466	71 475	71 483	71 492	71 500	71 508
519	71 517	71 525	71 533	71 542	71 550	71 559	71 567	71 575	71 584	71 592
520	71 600	71 609	71 617	71 625	71 634	71 642	71 650	71 659	71 667	71 675
521	71 684	71 692	71 700	71 709	71 717	71 725	71 734	71 742	71 750	71 759
522	71 767	71 775	71 784	71 792	71 800	71 809	71 817	71 825	71 834	71 842
523	71 850	71 858	71 867	71 875	71 883	71 892	71 900	71 908	71 917	71 925
524	71 933	71 941	71 950	71 958	71 966	71 975	71 983	71 991	71 999	71 008
525	72 016	72 024	72 032	72 041	72 049	72 057	72 066	72 074	72 082	72 090
526	72 099	72 107	72 115	72 123	72 132	72 140	72 148	72 156	72 165	72 173
527	72 181	72 189	72 198	72 206	72q214	72 222	72 230	72 239	72 247	72 255
528	72 263	72 272	72 280	72 288	73 296	72 304	72 313	72 321	72 329	72 337
529	72 346	72 354	72 362	72 370	72 378	72 387	72 395	72 403	72 411	72 419
530	72 428	72 436	72 444	72 452	72 460	72 469	72 477	72 485	72 493	72 501
531	72 509	72 518	72 526	72 534	72 542	72 550	72 558	72 567	72 575	72 583
532	72 591	72 599	72 607	72 616	72 624	72 632	72 640	72 648	72 656	72 665
533	673	72 681	72 689	72 697	72 705	72 713	72 722	72 730	72 738	72 746
534	72 754	72 762	72 770	72 779	72 787	72 795	72 803	72 811	72 819	72 827
535	72 835	72 843	72 852	72 860	72 868	72 876	72 884	72 892	72 900	72 908
536	72 916	72 925	72 933	72 941	72 949	72 957	72 965	72 973	72 981	72 989
537	72 997	73 006	73 014	73 022	73 030	73 038	72 046	73 054	73 062	73 070
538	73 078	73 086	73 094	73 102	73 111	73 119	73 127	73 135	73 143	73 151
539	73 159	73 167	73 175	73 183	73 191	73 199	73 207	73 215	73 223	73 231
540	73 239	73 247	73 255	73 263	73 272	73 280	73 288	73 296	73 304	73 312
541	73 320	73 328	73 336	73 344	73 352	73 360	73 368	73 376	73 384	73 392
542	73 400	73 408	73 416	73 424	73 432	73 440	73 448	73 456	73 464	73 472
543	73 480	73 488	73 496	73 504	73 512	73 520	73 528	73 536	73 544	73 552
544	73 560	73 568	73 576	73 584	73 592	73 600	73 608	73 616	73 624	73 632
545	73 640	73 648	73 656	73 664	73 672	73 679	73 687	73 695	73 703	73 711
546	73 719	73 727	73 735	73 743	73 751	73 759	73 767	73 775	73 783	73 791
547	73 799	73 807	73 815	73 823	73 830	73 838	73 846	73 854	73 862	73 870
548	73 878	73 886	73 894	73 902	73 910	73 918	73 926	73 933	73 941	73 919
549	73 957	73 965	73 973	73 981	73 989	73 997	74 005	74 013	74 020	74 028
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
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551	74 115	74 123	74 131	74 139	74 147	74 155	74 162	74 170	74 178	74 186
552	74 194	74 202	74 210	74 218	74 225	74 233	74 241	74 249	74 257	74 265
553	74 273	74 280	74 288	74 296	74 301	74 312	74 320	74 327	74 335	74 343
554	74 351	74 359	74 367	74 374	74 382	74 390	74 398	74 406	74 414	74 421
555	74 429	74 437	74 445	74 453	74 461	74 468	74 476	74 484	74 492	74 500
556	74 507	74 515	74 523	74 531	74 539	74 547	74 554	74 562	74 570	74 578
557	74 586	74 593	74 601	74 609	74 617	74 624	74 632	74 640	74 648	74 656
558	74 663	74 671	74 679	74 687	74 695	74 702	74 710	74 718	74 726	74 733
559	74 741	74 749	74 757	74 764	74 772	74 780	74 788	74 796	74 803	74 811
560	74 819	74 827	74 834	74 842	74 850	74 858	74 865	74 873	74 881	74 889
561	74 896	74 904	74 912	74 920	74 927	74 935	74 943	74 950	74 958	74 966
562	74 974	74 981	74 989	74 997	75 005	75 012	75 020	75 028	75 035	75 043
563	75 051	75 059	75 066	75 074	75 082	75 089	75 097	75 105	75 113	75 120
564	75 128	75 136	75 143	75 151	75 159	75 166	75 174	75 182	75 189	75 197
565	75 205	75 213	75 220	75 228	75 236	75 243	75 251	75 259	75 266	75 274
566	75 282	75 289	75 297	75 305	75 312	75 320	75 328	75 335	75 343	75 351
567	75 358	75 366	75 374	75 381	75 389	75 397	75 404	75 412	75 420	75 427
568	75 435	75 442	75 450	75 458	75 465	75 473	75 481	75 488	75 496	75 504
569	75511	75 519	75 526	75 534	75 542	75 549	75 557	75 565	75 572	75 580
570	75 587	75 595	75 603	75 610	75 618	75 626	75 633	75 641	75 648	75 656
571	75 664	75 671	75 679	75 686	75 694	75 702	75 709	75 717	75 724	75 732
572	75 740	75 747	75 755	75 762	75 770	75 778	75 785	75 793	75 800	75 808
573	75 815	75 823	75 831	75 838	75 846	75 853	75 861	75 868	75 876	75 884
574	75 891	75 899	75 906	75 914	75 921	75 929	75 937	75 944	75 952	75 959
575	75 967	75 974	75 982	75 989	75 997	76 005	76 012	76 020	76 027	76 035
576	76 042	76 050	76 057	76 065	76 072	76 080	76 087	76 095	76 103	76 110
577	76 118	76 125	76 133	76 140	76 148	76 155	76 163	76 170	76 178	76 185
578	76 193	76 200	76 208	76 215	76 223	76 230	76 238	76 245	76 253	76 260
579	76 268	76 275	76 283	76 290	76 298	76 305	76 313	76 320	76 328	76 335
580	76 343	76 350	76 358	76 365	76 373	76 380	76 388	76 395	76 403	76 410
581	76 418	76 425	76 433	76 440	76 448	76 455	76 462	76 470	76 477	76 485
582	76 492	76 500	76 507	76 515	76 522	76 530	76 537	76 545	76 552	76 559
583	76 567	76 574	76 582	76 589	76 597	76 604	76 612	76 619	76 626	76 634
584	76 641	76 649	76 656	76 664	76 671	76 678	76 686	76 693	76 701	76 708
585	76 716	76 723	76 730	76 738	76 745	76 753	76 760	76 768	76 775	76 782
586	76 790	76 797	76 805	76 812	76 819	76 827	76 834	76 842	76 849	76 856
587	76 864	76 871	76 879	76 886	76 893	76 901	76 908	76 916	76 923	76 930
588	76 938	76 945	76 953	76 960	76 967	76 975	76 982	76 989	76 997	77 004
589	77 012	77 019	77 026	77 034	77 041	77 048	77 056	77 063	77 070	77 078
590	77 085	77 093	77 100	77 107	77 115	77 122	77 129	77 137	77 144	77 151
591	77 159	77 166	77 173	77 181	77 188	77 195	77 129	77 210	77 217	77 225
592	77 232	77 240	77 247	77 254	77 262	77 269	77 276	77 283	77 291	77 298
593	77 305	77 313	77 320	77 327	77 335	77 342	77 349	77 357	77 364	77 371
594	77 379	77 386	77 393	77 401	77 408	77 415	77 422	77 430	77 437	77 444
595	77 452	77 459	77 466	77 474	77 481	77 488	77 495	77 503	77 510	77 517
596	77 525	77 532	77 539	77 546	77 554	77 561	77 568	77 576	77 583	77 590
597	77 597	77 605	77 612	77 619	77 627	77 634	77 641	77 648	77 656	77 663
598	77 670	77 677	77 685	77 692	77 699	77 706	77 714	77 721	77 728	77 735
599	77 743	77 750	77 757	77 764	77 772	77 779	77 786	77 793	77 801	77 808
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
600	77 815	77 822	77 830	77 837	77 844	77 851	77 859	77 866	77 873	77 880
601	77 887	77 895	77 902	77 909	77 916	77 924	77 931	77 938	77 915	77 952
602	77 960	77 967	77 974	77 981	77 988	77 996	78 003	78 010	78 017	78 025
603	78 032	78 0 9	78 046	78 053	78 061	78 068	78 075	78 082	78 089	78 097
604	78 104	78 111	78 118	78 125	78 132	78 140	78 147	78 154	78 161	78 168
605	78 176	78 183	78 190	78 197	78 204	78 211	78 219	78 226	78 233	78 240
606	78 247	78 254	78 262	78 269	78 276	78 283	78 290	78 297	78 305	78 312
607	78 319	78 326	78 333	78 340	78 347	78 355	78 362	78 369	78 376	78 383
608	78 390	78 398	78 405	78 412	78 419	78 426	78 433	78 440	78 447	78 455
609	78 462	78 469	78 476	78 483	78 490	78 497	78 504	78 512	78 519	78 526
610	78 533	78 540	78 547	78 554	78 561	78 569	78 576	78 583	78 590	78 597
611	78 604	78 611	78 618	78 625	78 633	78 640	78 647	78 654	78 661	78 668
612	78 675	78 682	78 689	78 696	78 704	78 711	78 718	78 725	78 732	78 739
613	78 746	78 753	78 760	78 767	78 774	78 781	78 789	78 796	78 803	78 810
614	78 817	78 824	78 831	78 838	78 845	78 852	78 859	78 866	78 873	78 880
615	78 888	78 895	78 902	78 909	78 916	78 923	78 930	78 937	78 944	78 951
616	78 958	78 965	78 972	78 979	78 986	78 993	79 000	79 007	79 014	78 021
617	79 029	79 036	79 043	79 050	79 057	78 064	79 071	79 078	79 085	79 092
618	79 099	79 106	79 113	79 120	79 127	78 134	79 141	79 148	79 155	79 162
619	79 169	79 176	79 183	79 190	79 197	79 204	79 211	79 218	79 225	79 232
620	79 239	79 246	79 253	79 260	79 267	79 274	79 281	79 288	79 295	79 302
621	79 309	79 316	79 323	79 330	79 337	79 344	79 351	79 358	79 365	79 372
622	79 379	79 386	79 393	79 400	79 407	79 414	79 421	79 428	79 435	79 442
623	79 449	79 456	79 463	79 470	79 477	79 484	79 491	79 498	79 505	79 511
624	79 518	79 525	79 532	79 539	79 546	79 553	79 560	79 567	79 574	79 581
625	79 588	79 595	79 602	79 609	79 616	79 623	79 630	79 637	79 644	79 650
626	79 657	79 664	79 671	79 678	79 685	79 692	79 699	79 706	79 713	79 720
627	79 727	79 734	79 741	79 748	79 754	79 761	79 768	79 775	79 782	79 789
628	79 796	79 803	79 810	79 817	79 824	79 831	79 837	79 844	79 851	79 858
629	79 865	79 872	79 879	79 886	79 893	79 900	79 906	79 913	79 920	79 927
630	79 934	79 941	79 948	79 955	79 962	79 969	79 975	79 982	79 989	79 996
631	80 003	80 010	80 017	80 024	80 030	80 037	80 044	80 051	80 058	80 065
632	80 072	80 079	80 085	80 092	80 099	80 106	80 113	80 120	80 127	80 134
633	80 140	80 147	80 154	80 161	80 168	80 175	80 182	80 188	80 195	80 202
634	80 209	80 216	80 223	80 229	80 236	80 243	80 250	80 257	80 264	80 271
635	80 277	80 284	80 291	80 298	80 305	80 312	80 318	80 325	80 332	80 339
636	80 346	80 353	80 359	80 366	80 373	80 380.	80 387	80 393	80 400	80 407
637	80 414	80 421	80 428	80 434	80 441	80 448	80 455	80 462	80 468	80 475
638	80 482	80 489	80 496	80 502	80 509	80 516	80 523	80 530	80 536	80 543
639	80 550	80 557	80 564	80 570	80 577	80 584	80 591	80 598	80 604	80 611
640	80 618	80 625	80 632	80 638	80 645	80 652	80 659	80 665	80 672	80 679
641	80 686	80 693	80 699	80 706	80 713	80 720	80 726	80 733	80 740	80 747
642	80 754	80 760	80 767	80 774	80 781	80 787	80 794	80 801	80 808	80 814
643	80 821	80 828	80 835	80 841	80 848	80 855	80 862	80 868	80 875	80 882
644	80 889	80 895	80 902	80 909	80 916	80 922	80 929	80 936	80 943	80 949
645	80 956	80 963	80 969	80 976	80 983	80 990	80 996	81 003	81 010	81 017
646	81 023	81 030	81 037	81 043	81 050	81 057	81 064	81 070	81 077	81 084
647	81 090	81 097	81 104	81 111	81 117	81 124	81 131	81 137	81 144	81 151
648	81 158	81 164	81 171	81 178	81 181	81 191	81 198	81 204	81 211	81 218
649	81 224	81 231	81 238	81 245	81 251	81 258	81 265	81 271	81 278	81 285
No.	0	1	2	3	4	5	6	7	8	9

No.	0	1	2	3	4	5	6	7	8	9
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651	81 358	81 365	81 371	81 378	81 385	81 391	81 398	81 405	81 411	81 418
652	81 425	81 431	81 438	81 445	81 451	81 458	81 465	81 471	81 478	81 485
653	81 491	81 498	81 505	81 511	81 518	81 525	81 531	81 538	81 544	81 551
654	81 558	81 564	81 571	81 578	81 584	81 591	81 598	81 604	81 611	81 617
655	81 624	81 631	81 637	81 644	81 651	81 657	81 664	81 671	81 677	81 681
656	81 690	81 697	81 704	81 710	81 717	81 723	81 730	81 737	81 743	81 750
657	81 757	81 763	81 770	81 776	81 783	81 790	81 796	81 803	81 809	81 816
658	81 823	81 829	81 836	81 842	81 849	81 856	81 862	81 869	81 875	81 882
659	81 889	81 895	81 902	81 908	81 915	81 921	81 928	81 935	81 941	81 948
660	81 954	81 961	81 968	81 974	81 981	81 987	81 994	82 000	82 007	82 014
661	82 020	82 027	82 033	82 040	82 046	82 053	82 060	82 066	82 073	82 079
662	82 086	82 092	82 099	82 105	82 112	82 119	82 125	82 132	82 138	82 145
663	82 151	82 158	82 164	82 171	82 178	82 184	82 191	82 197	82 204	82 210
664	82 217	82 223	82 230	82 236	82 243	82 249	82 256	82 263	82 269	82 276
665	82 282	82 289	82 295	82 302	82 308	82 315	82 321	82 328	82 334	82 341
666	82 347	82 354	82 360	82 367	82 373	82 380	82 387	82 393	82 400	82 406
667	82 413	82 419	82 426	82 432	82 439	82 445	82 452	82 458	82 465	82 471
668	82 478	82 484	82 491	82 497	82 504	82 510	82 517	82 523	82 530	82 536
669	82 543	82 549	82 556	82 562	82 569	82 575	82 582	82 588	82 595	82 601
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671	82 672	82 679	82 685	82 692	82 698	82 705	82 711	82 718	82 724	82 730
672	82 737	82 743	82 750	82 756	82 763	82 769	82 776	82 782	82 789	82 795
673	82 802	82 808	82 814	82 821	82 827	82 834	82 840	82 847	82 853	82 860
674	82 866	82 872	82 879	82 885	82 892	82 898	82 905	82 911	82 918	82 924
675	82 930	82 937	82 943	82 950	82 956	82 963	82 969	82 975	82 982	82 988
676	82 995	83 001	83 008	83 014	83 020	83 027	83 033	83 040	83 046	83 052
677	83 059	83 065	83 072	83 078	83 085	83 091	83 097	83 104	83 110	83 117
678	83 123	83 129	83 136	83 142	83 149	83 155	83 161	83 168	83 174	83 181
679	83 187	83 193	83 200	83 206	83 213	83 219	83 225	83 232	83 238	83 245
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681	83 315	83 321	83 327	83 334	83 340	83 347	83 353	83 359	83 366	83 372
682	83 378	83 385	83 391	83 398	83 404	83 410	83 417	83 423	83 429	83 436
683	83 442	83 448	83 455	83 461	83 467	83 474	83 480	83 487	83 493	83 499
684	83 506	83 512	83 518	83 525	83 531	83 537	83 544	83 550	83 556	83 563
685	83 569	83 575	83 582	83 588	83 594	83 601	83 607	83 613	83 620	83 626
686	83 632	83 639	83 645	83 651	83 658	83 664	83 670	83 677	83 683	83 689
687	83 696	83 702	83 708	83 715	83 721	83 727	83 734	83 740	83 746	83 753
688	83 759	83 765	83 771	83 778	83 784	83 790	83 797	83 803	83 809	83 816
689	83 822	83 828	83 835	83 841	83 847	83 853	83 860	83 866	83 872	83 879
690	83 885	83 891	83 897	83 904	83 910	83 916	83 923	83 929	83 935	83 942
691	83 948	83 954	83 960	83 967	83 973	83 979	83 985	83 992	83 998	84 004
692	84 011	84 017	84 023	84 029	84 036	84 042	84 048	84 055	84 061	84 067
693	84 073	84 080	84 086	84 092	84 098	84 105	84 111	84 117	84 123	84 130
694	84 136	84 142	84 148	84 155	84 161	84 167	84 173	84 180	84 186	84 192
695	84 198	84 205	84 211	84 217	84 223	84 230	84 236	84 242	84 248	84 255
696	84 261	84 267	84 273	84 280	84 286	84 292	84 298	84 305	84 311	84 317
697	84 323	84 330	84 336	84 342	84 348	84 354	84 361	84 367	84 373	84 379
698	84 386	84 392	84 398	84 404	84 410	84 417	84 423	84 429	84 435	84 442
699	84 448	84 454	84 460	84 466	84 473	84 479	84 485	84 491	84 497	84 504
No.	0	1	2	3	4	5	6	7	8	9

No.	0	1	2	3	4	5	6	7	8	9
700	84 510	84 516	84 522	84 528	84 535	84 541	84 547	84 553	84 559	84 566
701	84 572	84 578	84 584	84 590	84 597	84 603	84 609	84 615	84 621	84 628
702	84 634	84 640	84 646	84 652	84 658	84 665	84 671	84 677	84 683	84 689
703	84 696	84 702	84 708	84 714	84 720	84 726	84 733	84 739	84 745	84 751
704	84 757	84 763	84 770	84 776	84 782	84 788	84 794	84 800	84 807	84 813
705	84 819	84 825	84 831	84 837	84 844	84 850	84 856	84 862	84 868	84 874
706	84 880	84 887	84 893	84 899	84 905	84 911	84 917	84 924	84 930	84 936
707	84 942	84 948	84 954	84 960	84 967	84 973	84 979	84 985	84 991	84 997
708	85 003	85 009	85 016	85 022	85 028	85 034	85 040	85 046	85 052	85 058
709	85 065	85 071	85 077	85 083	85 080	85 095	85 101	85 107	85 114	85 120
710	85 126	85 132	85 138	85 144	85 150	85 156	85 163	85 169	85 175	85 181
711	85 187	85 193	85 199	85 205	85 211	85 217	85 224	85 230	85 236	85 242
712	85 248	85 254	85 260	85 266	85 272	85 278	85 285	85 291	85 297	85 303
713	85 309	85 315	85 321	85 327	85 333	85 339	85 345	85 352	85 358	85 364
714	85 370	85 376	85 382	85 388	85 394	85 400	85 406	85 412	85 418	85 425
715	85 431	85 437	85 443	85 449	85 455	85 461	85 467	85 473	85 479	85 485
716	85 491	85 497	85 503	85 509	85 516	85 522	85 528	85 534	85 540	85 546
717	85 552	85 558	85 564	85 570	85 576	85 582	85 588	85 594	85 600	85 606
718	85 612	85 618	85 625	85 631	85 637	85 643	85 649	85 655	85 61	85 667
719	85 673	85 679	85 685	85 691	85 697	85 703	85 709	85 715	85 721	85 727
720	85 733	85 739	85 745	85 751	85 757	85 763	85 769	85 775	85 781	85 788
721	85 794	85 800	85 806	85 812	85 818	85 824	85 830	85 836	85 842	85 848
722	85 854	85 860	85 866	85 872	85 878	85 884	85 890	85 896	85 902	85 908
723	85 914	85 920	85 926	85 932	85 938	85 944	85 950	85 956	85 962	85 968
724	85 974	85 980	85 986	85 992	85 998	86 004	86 010	86 016	86 022	86 028
725	86 034	86 040	86 046	86 052	86 058	86 064	86 070	86 076	86 082	86 088
726	86 094	86 100	86 106	86 112	86 118	86 124	86 130	86 136	86 141	86 147
727	86 153	86 159	86 165	86 171	86 177	86 183	86 189	86 195	86 201	86 207
728	86 213	86 219	86 225	86 231	86 237	86 243	86 249	86 255	86 261	86 267
729	86 273	86 279	86 285	86 291	86 297	86 303	86 308	86 314	86 320	86 326
730	86 332	86 338	86 344	86 350	86 356	86 362	86 368	86 374	86 380	86 386
731	86 392	86 398	86 404	86 410	86 415	86 421	86 427	86 433	86 439	86 445
732	86 451	86 457	86 463	86 469	86 475	86 481	86 487	86 493	86 499	86 504
733	86 510	86 516	86 522	86 528	86 534	86 540	86 546	86 552	86 558	86 564
734	86 570	86 576	86 581	86 587	86 593	86 599	86 605	86 611	86 617	86 623
735	86 629	86 635	86 641	86 646	86 652	86 658	86 664	86 670	86 676	86 682
736	86 688	86 694	86 700	86 705	86 711	86 717	86 723	86 729	86 735	86 741
737	86 747	86 753	86 759	86 764	86 770	86 776	86 782	86 788	86 794	86 800
738	86 806	86 812	86 817	86 823	86 829	86 835	86 841	86 847	86 853	86 859
739	86 864	86 870	86 876	86 882	86 888	86 894	86 900	86 906	86 911	86 917
740	86 923	86 929	86 935	86 941	86 947	86 953	86 958	86 964	86 970	86 976
741	86 982	86 988	86 994	86 999	87 005	87 011	87 017	87 023	87 970	87 035
742	87 040	87 046	87 052	87 058	87 064	87 070	87 075	87 081	87 087	87 093
743	87 099	87 105	87 111	87 116	87 122	87 128	87 134	87 140	87 146	87 151
744	87 157	87 163	87 169	87 175	87 181	87 186	87 192	87 198	87 204	87 210
745	87 216	87 221	87 227	87 233	87 239	87 245	87 251	87 256	87 262	87 268
746	87 274	87 280	87 286	87 291	87 297	87 303	87 309	87 315	87 320	87 326
747	87 332	87 338	87 344	87 349	87 355	87 361	87 367	87 373	87 379	87 384
748	87 390	87 396	87 402	87 408	87 413	87 419	87 425	87 431	87 437	87 442
749	87 448	87 454	87 460	87 466	87 471	87 477	87 483	87 489	87 495	87 500
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
750	87 506	87 512	87 518	87 523	87 529	87 535	87 541	87 547	87 552	87 558
751	87 564	87 570	87 576	87 581	87 587	87 593	87 599	87 604	87 610	87 616
752	87 622	87 628	87 633	87 639	87 645	87 651	87 656	87 662	87 668	87 674
753	87 679	87 685	87 691	87 697	87 703	87 708	87 714	87 720	87 726	87 731
754	87 737	87 743	87 749	87 754	87 760	87 766	87 772	87 777	87 783	87 789
755	87 795	87 800	87 806	87 812	87 818	87 823	87 829	87 835	87 841	87 846
756	87 852	87 858	87 864	87 869	87 875	87 881	87 887	87 892	87 898	87 904
757	87 910	87 915	87 921	87 927	87 933	87 938	87 944	87 950	87 955	87 961
758	87 967	87 973	87 978	87 984	87 990	87 996	88 001	88 007	88 013	88 018
759	88 024	88 030	88 036	88 041	88 047	88 053	88 058	88 064	88 070	88 076
760	88 081	88 087	88 093	88 098	88 104	88 110	88 116	88 121	88 127	88 133
761	88 138	88 144	88 150	88 156	88 161	88 167	88 173	88 178	88 184	88 190
762	88 195	88 201	88 207	88 213	88 218	88 224	88 230	88 235	88 241	88 247
763	88 252	88 258	88 264	88 270	88 275	88 281	88 287	88 292	88 298	88 304
764	88 309	88 315	88 321	88 326	88 332	88 338	88 343	88 349	88 355	88 360
765	88 366	88 372	88 377	88 383	88 389	88 395	88 400	88 406	88 412	88 417
766	88 423	88 429	88 434	88 440	88 446	88 451	88 457	88 463	88 468	88 474
767	88 480	88 485	88 491	88 497	88 502	88 508	88 513	88 519	88 525	88 530
768	88 536	88 542	88 547	88 553	88 559	88 564	88 570	88 576	88 581	88 587
769	88 593	88 598	88 604	88 610	88 615	88 621	88 627	88 632	88 638	88 643
770	88 649	88 655	88 660	88 666	88 672	88 677	88 683	88 689	88 694	88 700
771	88 705	88 711	88 717	88 722	88 728	88 734	88 739	88 745	88 750	88 756
772	88 762	88 767	88 773	88 779	88 784	88 790	88 795	88 801	88 807	88 812
773	88 818	88 824	88 829	88 835	88 840	88 846	88 852	88 857	88 863	88 868
774	88 874	88 880	88 885	88 891	88 897	88 902	88 908	88 913	88 919	88 925
775	88 930	88 936	88 941	88 947	88 953	88 958	88 964	88 969	88 975	88 981
776	88 896	88 992	88 997	89 003	89 009	89 014	89 020	89 025	89 031	89 037
777	89 042	89 048	89 053	89 059	89 064	89 070	89 076	89 081	89 087	89 092
778	89 098	89 104	89 109	89 115	89 120	89 126	89 131	89 137	89 143	89 148
770	89 154	89 159	89 165	89 170	89 176	89 182	89 187	89 193	89 198	89 204
780	89 209	89 215	89 221	89 226	89 232	89 237	89 243	89 248	89 254	89 260
781	89 265	89 271	89 276	89 282	89 287	89 293	89 298	89 304	89 310	89 315
782	89 321	89 326	89 332	89 337	89 343	89 348	89 354	89 360	89 365	89 371
783	89 376	89 382	89 387	89 393	89 398	89 404	89 409	89 415	89 421	89 426
784	89 432	89 437	89 443	89 448	89 454	89 459	89 465	89 470	89 476	89 481
785	89 487	89 492	89 498	89 504	89 509	89 515	89 520	89 526	89 531	89 537
786	89 542	89 548	89 553	89 559	89 564	89 570	89 575	89 581	89 586	89 592
787	89 597	89 603	89 609	89 614	89 620	89 625	89 631	89 636	89 642	89 647
788	89 653	89 658	89 664	89 669	89 675	89 680	89 686	89 691	89 97	89 702
789	89 708	89 713	89 719	89 724	89 730	89 735	89 741	89 746	89 752	89 757
790	89 763	89 768	89 774	89 779	89 785	89 790	89 796	89 801	89 807	89 812
791	89 818	89 823	89 829	89 834	89 840	89 845	89 851	89 856	89 862	89 867
892	89 873	89 878	89 883	89 889	89 894	89 900	89 905	89 911	89 916	89 922
793	89 927	89 933	89 938	89 944	89 949	89 955	89 960	89 966	89 971	89 977
794	89 982	89 988	89 993	89 998	90 004	90 009	90 015	90 020	90 026	90 031
795	90 037	90 042	90 048	90 053	90 059	90 064	90 069	90 075	90 080	90 086
796	90 091	90 097	90 102	90 108	90 113	90 119	90 124	90 129	90 135	90 140
797	90 146	90 151	90 157	90 162	90 168	90 173	90 179	90 184	90 189	90 195
798	90 200	90 206	90 211	90 217	90 222	90 227	90 233	90 238	90 244	90 249
799	90 255	90 260	90 266	90 271	90 276	90 282	90 287	90 293	90 298	90 304
No.	0	1	2	3	4	5	6	7	8	9

No.	0	1	2	3	4	5	6	7	8	9
800	90 309	90 311	90 320	90 325	90 331	90 336	90 342	90 347	90 352	90 358
801	90 363	90 369	90 374	90 380	90 385	90 390	90 396	90 401	90 407	90 412
802	90 417	90 423	90 428	90 434	90 439	90 445	90 450	90 455	90 461	90 466
803	90 472	90 477	90 482	90 488	90 493	90 499	90 504	90 509	90 515	90 520
804	90 526	90 531	90 536	90 542	90 547	90 553	90 558	90 563	90 569	90 571
805	90 580	90 585	90 590	90 596	90 601	90 607	90 612	90 617	90 623	90 628
806	90 634	90 639	90 644	90 650	90 655	90 660	90 666	90 671	90 677	90 682
807	90 687	90 693	90 698	90 703	90 709	90 714	90 720	90 725	90 730	90 736
808	90 741	90 747	90 752	90 757	90 763	90 768	90 773	90 779	90 784	90 789
809	90 795	90 800	90 806	90 811	90 816	90 822	90 827	90 832	90 838	90 843
810	90 849	90 854	90 859	90 865	90 870	90 875	90 881	90 886	90 891	90 897
811	90 902	90 907	90 913	90 918	90 924	90 929	90 934	90 940	90 945	90 950
812	90 956	90 961	90 966	90 972	90 977	90 982	90 988	90 993	90 998	91 004
813	91 009	91 014	91 020	91 025	91 030	91 036	91 041	91 046	91 052	91 057
814	91 062	91 068	91 073	91 078	91 084	91 089	91 094	91 100	91 105	91 110
815	91 116	91 121	91 126	91 132	91 137	91 142	91 148	91 153	91 158	91 164
816	91 169	91 174	91 180	91 185	91 190	91 196	91 201	91 206	91 212	91 217
817	91 222	91 228	91 233	91 238	91 243	91 249	91 254	91 259	91 265	91 270
818	91 275	91 281	91 286	91 291	91 297	91 302	91 307	91 312	91 318	91 323
819	91 328	91 334	91 339	91 344	91 350	91 355	91 360	91 365	91 371	91 376
820	91 381	91 387	91 392	91 397	91 403	91 408	91 413	91 418	91 424	91 429
821	91 434	91 440	91 445	91 450	91 455	91 461	91 466	91 471	91 477	91 482
822	91 487	91 492	91 498	91 503	91 508	91 514	91 519	91 524	91 529	91 535
823	91 540	91 545	91 551	91 556	91 561	91 566	91 572	91 577	91 582	91 587
824	91 593	91 598	91 603	91 609	91 614	91 619	91 624	91 630	91 635	91 640
825	91 645	91 651	91 656	91 661	91 666	91 672	91 677	91 682	91 687	91 693
826	91 698	91 703	91 709	91 714	91 719	91 724	91 730	91 735	91 740	91 745
827	91 751	91 756	91 761	91 766	91 772	91 777	91 782	91 787	91 793	91 798
828	91 803	91 808	91 814	91 819	91 824	91 829	91 834	91 840	91 845	91 850
829	91 855	91 861	91 866	91 871	91 876	91 882	91 887	91 892	91 897	91 903
830	91 908	91 913	91 918	91 924	91 929	91 934	91 939	91 944	91 950	91 955
831	91 960	91 965	91 971	91 976	91 981	91 986	91 991	91 997	92 002	92 007
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833	92 065	92 070	92 075	92 080	92 085	92 091	92 096	92 101	92 106	92 111
834	92 117	92 122	92 127	92 132	92 137	92 143	92 148	92 153	92 158	92 163
835	92 169	92 174	92 179	92 184	92 189	92 195	92 200	92 205	92 210	92 215
836	92 221	92 226	92 231	92 236	92 241	92 247	92 252	92 257	92 262	92 267
837	92 273	92 278	92 283	92 288	92 293	92 298	92 304	92 309	92 314	92 319
838	92 324	92 330	92 335	92 340	92 345	92 350	92 355	92 361	92 366	92 371
839	92 376	92 381	92 387	92 392	92 397	92 402	92 407	92 412	92 418	92 423
840	92 428	92 433	92 438	92 443	92 449	92 454	92 459	92 464	92 469	92 474
841	92 480	92 485	92 490	92 495	92 500	92 505	92 511	92 516	92 521	92 526
842	92 531	92 536	92 542	92 547	92 552	92 557	92 562	92 567	92 572	92 578
843	92 583	92 588	92 593	92 598	92 603	92 609	92 614	92 619	92 624	92 629
844	92 634	92 639	92 645	92 650	92 655	92 660	92 665	92 670	92 675	92 681
845	92 686	92 691	92 696	92 701	92 706	92 711	92 716	92 722	92 727	92 732
846	92 737	92 742	92 747	92 752	92 758	92 763	92 768	92 773	92 778	92 783
847	92 788	92 793	92 799	92 804	92 809	92 814	92 819	92 824	92 829	92 834
848	92 840	92 845	92 850	92 855	92 860	92 865	92 870	92 875	92 881	92 886
849	92 891	92 896	92 901	92 906	92 911	92 916	92 921	92 927	92 932	92 937
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
850	92 942	92 947	92 952	92 957	92 962	92 967	92 973	92 978	92 983	92 988
851	92 993	92 998	93 003	93 008	93 013	93 018	93 024	93 029	93 034	93 0 9
852	93 044	93 049	93 054	93 059	93 064	93 069	93 075	93 080	93 085	93 090
853	93 095	93 100	93 105	93 110	93 115	93 120	93 125	93 131	93 136	93 141
854	93 146	93 151	93 156	93 161	93 166	93 171	93 176	93 181	93 186	93 192
855	93 197	93 202	93 207	93 212	93 217	93 222	93 227	93 232	93 237	93 242
856	93 247	93 252	93 258	93 263	93 268	93 273	93 278	93 283	93 288	93 293
857	93 298	93 303	93 308	93 313	93 318	93 323	93 328	93 334	93 339	93 344
858	93 349	93 354	93 359	93 364	93 369	93 374	93 379	93 384	93 389	93 394
859	93 399	93 404	93 409	93 414	93 420	93 425	93 430	93 435	93 440	93 445
860	93 450	93 455	93 460	93 465	93 470	93 475	93 480	93 485	93 490	93 495
861	93 500	93 505	93 510	93 515	93 520	93 526	93 531	93 536	93 541	93 546
862	93 551	93 556	93 561	93 566	93 571	93 576	93 581	93 586	93 591	93 596
863	93 601	93 606	93 611	93 616	93 621	93 626	93 631	93 636	93 641	93 646
864	93 651	93 656	93 661	93 666	93 671	93 676	93 682	93 687	93 692	93 697
865	93 702	93 707	93 712	93 717	93 722	93 727	93 732	93 737	93 742	93 747
866	93 752	93 757	93 762	93 767	93 772	93 777	93 782	93 787	93 792	93 797
867	93 802	93 807	93 812	93 817	93 822	93 827	93 832	93 837	93 842	93 847
868	93 852	93 857	93 862	93 867	93 872	93 877	93 882	93 887	93 892	93 897
869	93 902	93 907	93 912	93 917	93 922	93 927	93 932	93 937	93 942	93 947
870	93 952	93 957	93 962	93 967	93 972	93 977	93 982	93 987	93 992	93 997
871	94 002	94 997	94 012	94 017	94 022	94 027	94 032	94 037	94 042	94 047
872	94 052	94 057	94 ;62	94 067	94 072	94 077	94 082	94 086	94 091	94 096
873	94 101	94 106	94 111	94 116	94 121	94 126	94 131	94 136	94 141	94 146
874	94 151	94 156	94 161	94 166	94 171	94 176	94 181	94 186	94 191	94 196
875	94 201	94 206	94 211	94 216	94 221	94 226	94 231	94 236	94 240	94 245
876	94 250	94 255	94 260	94 265	94 270	94 275	94 280	94 285	94 290	94 295
877	94 300	94 305	94 310	94 315	94 320	94 325	94 330	94 335	94 340	94 345
878	94 349	94 354	94 359	94 364	94 369	94 374	94 379	94 384	94 389	94 394
879	94 399	94 404	94 409	94 414	94 419	94 424	94 429	94 433	94 438	94 443
880	94 448	94 453	94 458	94 463	94 468	94 473	94 478	94 483	94 488	94 493
881	94 498	94 503	94 507	94 512	94 517	94 522	94 527	94 532	94 537	94 542
882	94 547	94 552	94 557	94 562	94 567	94 571	94 576	94 581	94 586	94 591
883	94 596	94 601	94 606	94 611	94 616	94 621	94 626	94 630	94 635	94 640
884	94 645	94 650	94 655	94 660	94 665	94 670	94 675	94 680	94 685	94 689
885	94 694	94 699	94 704	94 709	94 714	94 719	94 724	94 729	94 734	94 738
886	94 743	94 748	94 753	94 758	94 763	94 768	94 773	94 778	94 783	94 787
887	94 792	94 797	94 802	94 807	94 812	94 817	94 822	94 827	94 832	94 836
888	94 841	94 846	94 851	94 856	94 861	94 866	94 871	94 876	94 880	94 885
889	94 890	94 895	94 900	94 905	94 910	94 915	94 919	94 924	94 929	94 934
890	94 939	95 187	94 949	94 954	94 959	94 963	94 968	94 973	94 978	94 983
891	94 988	95 236	94 998	95 002	95 007	95 012	95 017	95 022	95 027	95 032
892	95 036	95 284	95 046	95 051	95 056	95 061	95 066	95 071	95 075	95 080
893	95 085	95 332	95 095	95 100	95 105	95 109	95 114	95 119	95 124	95 129
894	95 134	95 381	95 143	95 148	95 153	95 158	95 163	95 168	95 173	95 177
895	95 182	94 944	95 192	95 197	95 202	95 207	95 211	95 216	95 221	95 226
896	95 231	94 993	95 240	95 245	95 250	95 255	95 260	95 265	95 270	95 274
897	95 279	95 041	95 289	95 294	95 299	95 303	95 308	95 313	95 318	95 323
898	95 328	95 090	95 337	95 342	95 347	95 352	95 357	95 361	95 366	95 371
899	95 376	95 139	95 386	95 390	95 395	95 400	95 405	95 410	95 415	95 419
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
900	95 424	95 429	95 431	95 439	95 414	95 418	95 453	95 458	95 463	95 468
901	95 472	95 477	95 482	95 487	95 492	95 497	95 501	95 506	95 511	95 516
902	95 521	95 525	95 530	95 535	95 540	95 545	95 550	95 554	95 559	95 561
903	95 569	95 574	95 578	95 583	95 588	95 593	95 598	95 602	95 607	95 612
904	95 617	95 622	95 626	95 631	95 636	95 611	95 646	95 650	95 655	95 660
905	95 665	95 670	95 674	95 679	95 684	95 689	95 694	95 698	95 703	95 708
906	95 713	95 718	95 722	95 727	95 732	95 737	95 712	95 746	95 751	95 756
907	95 761	95 766	95 770	95 775	95 780	95 785	95 789	95 794	95 799	95 801
908	95 809	95 813	95 818	95 823	95 828	95 832	95 837	95 842	95 847	95 852
909	95 856	95 861	95 866	95 871	95 875	95 880	95 885	95 890	95 895	95 899
910	95 904	95 909	95 914	95 918	95 923	95 928	95 933	95 938	95 942	95 947
911	95 952	95 957	95 961	95 966	95 971	95 976	95 980	95 985	95 990	95 995
912	95 999	95 004	96 009	96 014	96 019	96 023	96 028	96 033	96 038	96 042
913	96 017	96 052	96 057	96 061	96 066	96 071	96 076	96 080	96 085	96 090
914	96 095	96 099	96 104	96 109	96 114	96 118	96 123	96 128	96 133	96 137
915	96 142	96 147	96 152	96 156	96 161	96 166	96 171	96 175	96 180	96 185
916	96 190	96 194	96 199	96 204	96 209	96 213	96 218	96 223	96 227	96 232
917	96 237	96 242	96 216	96 251	96 256	96 261	96 265	96 270	96 275	96 280
918	96 284	96 289	96 294	96 298	96 303	96 308	96 313	96 317	96 322	96 327
919	96 332	96 336	96 341	96 346	96 350	96 355	96 360	96 365	96 369	96 374
920	96 379	96 384	96 388	96 393	96 398	96 402	96 407	96 412	96 417	96 421
921	96 426	96 431	96 435	96 440	96 445	96 450	96 454	96 459	96 464	96 468
922	96 473	96 478	96 483	96 487	96 492	96 497	96 501	96 506	96 511	96 515
923	96 520	96 525	96 530	96 534	96 539	96 544	96 548	96 553	96 558	96 562
924	96 567	96 572	96 577	96 581	96 586	96 591	96 595	96 600	96 605	96 609
925	96 614	96 619	96 624	96 628	96 633	96 638	96 612	96 647	96 652	96 656
926	96 661	96 666	96 670	96 675	96 680	96 685	96 689	96 694	96 699	96 703
927	96 708	96 713	96 717	96 722	96 727	96 731	96 736	96 741	96 745	96 750
928	96 755	96 759	96 764	96 769	96 774	96 778	96 783	96 788	96 792	96 797
929	96 802	96 806	96 811	96 816	96 820	96 825	96 830	96 834	96 839	96 844
930	96 848	96 853	96 858	96 862	96 867	96 872	96 876	96 881	96 886	96 890
931	96 895	96 900	96 904	96 909	96 914	96 918	96 923	96 928	96 932	96 937
932	96 942	96 946	96 951	96 956	96 960	96 965	96 970	96 974	96 979	96 984
933	96 988	96 993	96 997	97 002	97 007	97 011	97 016	97 021	97 025	97 030
934	97 035	97 039	97 044	97 049	97 053	97 058	97 063	97 067	97 072	97 077
935	97 081	97 086	97 090	97 095	97 100	97 104	97 109	97 114	97 118	97 123
936	97 128	97 132	97 137	97 142	97 146	97 151	97 155	97 160	97 165	97 169
937	97 174	97 179	97 183	97 188	97 192	97 197	97 202	97 206	97 211	97 216
938	97 220	97 225	97 230	97 234	97 239	97 243	97 248	97 253	97 257	97 262
939	97 267	97 271	97 276	97 280	97 285	97 290	97 294	97 299	97 304	97 308
940	97 313	97 317	97 322	97 327	97 331	97 336	97 340	97 345	97 350	97 354
941	97 359	97 364	97 368	97 373	97 377	97 382	97 387	97 391	97 396	97 400
942	97 405	97 410	97 414	97 419	97 424	97 428	97 433	97 437	97 442	97 447
943	97 451	97 456	97 460	97 465	97 470	97 474	97 479	97 483	97 488	97 493
944	97 497	97 502	97 506	97 511	97 516	97 520	97 525	97 529	97 534	97 539
945	97 543	97 548	97 552	97 557	97 562	97 566	97 571	97 575	97 580	97 585
946	97 589	97 594	97 598	97 603	97 607	97 612	97 617	97 575	97 626	97 630
947	97 635	97 640	97 644	97 649	97 653	97 658	97 663	97 667	97 672	97 676
948	97 681	97 685	97 690	97 695	97 699	97 704	97 708	97 713	97 717	97 722
949	97 727	97 731	97 736	97 740	97 745	97 749	97 754	97 759	97 763	97 768
No.	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**

No.	0	1	2	3	4	5	6	7	8	9
950	97 772	97 777	97 782	97 786	97 791	97 795	97 800	97 804	97 809	97 813
951	97 818	97 823	97 827	97 832	97 836	97 841	97 815	97 850	97 855	97 859
952	97 861	97 8 8	97 873	97 877	97 882	97 886	97 891	97 896	97 900	97 905
953	97 909	97 914	97 918	97 923	97 928	97 932	97 937	97 941	97 946	97 950
954	97 955	97 959	97 964	97 968	97 973	97 978	97 982	97 987	97 991	97 996
955	98 000	98 005	98 009	98 014	98 019	98 023	98 028	98 032	98 037	98 041
956	98 016	98 050	98 055	98 059	98 064	98 068	98 073	98 078	98 082	98 087
957	98 091	98 096	98 100	98 105	98 109	98 114	98 118	98 123	98 127	98 132
958	98 137	98 141	98 146	98 150	98 155	98 159	98 164	98 168	98 173	98 177
959	98 182	98 186	98 191	98 195	98 200	98 204	98 209	98 214	98 218	98 223
960	98 227	98 2 2	98 236	98 241	98 245	98 250	98 254	98 259	98 263	98 268
961	98 272	98 277	98 281	98 286	98 290	98 295	98 299	98 304	98 308	98 313
962	98 318	98 322	98 327	98 331	98 336	98 340	98 345	98 349	98 354	98 358
963	98 363	98 367	98 372	98 376	98 381	98 385	98 390	98 394	98 399	98 403
964	98 408	98 412	98 417	98 421	98 426	98 430	98 435	98 439	98 444	98 448
965	98 453	98 457	98 462	98 466	98 471	98 475	98 480	98 484	98 489	98 493
966	98 498	98 502	98 507	98 511	98 516	98 520	98 525	98 529	98 534	98 538
967	98 543	98 547	98 552	98 556	98 561	98 565	98 570	98 574	98 579	98 583
968	98 588	98 592	98 597	98 601	98 605	98 610	98 614	98 619	98 623	98 628
969	98 632	98 637	98 641	98 646	98 650	98 655	98 659	98 664	98 668	98 673
970	98 677	98 682	98 686	98 691	98 695	98 700	98 704	98 709	98 713	98 717
971	98 722	98 726	98 731	98 735	98 740	98 744	98 749	98 753	98 758	98 762
972	98 767	98 771	98 776	98 780	98 784	98 789	98 793	98 798	98 802	98 807
973	98 811	98 816	98 820	98 825	98 829	98 834	98 838	98 843	98 847	98 851
974	98 856	98 860	98 865	98 869	98 874	98 878	98 883	98 887	98 892	98 896
975	98 900	98 905	98 909	98 914	98 918	98 923	98 927	98 932	98 936	98 941
976	98 945	98 949	98 954	98 958	98 963	98 967	98 972	98 976	98 981	98 985
977	98 989	98 994	98 998	99 003	99 007	99 012	99 016	99 021	99 025	99 029
978	99 034	99 038	99 043	99 047	99 052	99 056	99 061	99 065	99 069	99 074
979	99 078	99 083	99 087	99 092	99 096	99 100	99 105	99 109	99 114	99 118
980	99 123	99 127	99 131	99 136	99 140	99 145	99 149	99 154	99 158	99 162
981	99 167	99 171	99 176	99 180	99 185	99 189	99 193	99 198	99 202	99 207
982	99 211	99 216	99 220	99 224	99 229	99 233	99 238	99 242	99 247	99 251
983	99 255	99 260	99 264	99 269	99 273	99 277	99 282	99 286	99 291	99 295
984	99 300	99 304	99 308	99 313	99 317	99 322	99 326	99 330	99 335	99 339
985	99 344	99 348	99 352	99 357	99 361	99 366	99 370	99 374	99 379	99 383
986	99 388	99 392	99 396	99 401	99 405	99 410	99 414	99 419	99 423	99 427
987	99 432	99 436	99 441	99 445	99 449	99 454	99 458	99 463	99 467	99 471
988	99 476	99 480	99 484	99 489	99 493	99 498	99 502	99 506	99 511	99 515
989	99 520	99 524	99 528	99 533	99 537	99 542	99 546	99 550	99 555	99 559
990	99 564	99 568	99 572	99 577	99 581	99 585	99 590	99 594	99 599	99 603
991	99 607	99 612	99 616	99 621	99 625	99 629	99 634	99 638	99 642	99 647
992	99 651	99 656	99 660	99 664	99 669	99 673	99 677	99 682	99 686	99 691
993	99 695	99 699	99 704	99 708	99 712	99 717	99 721	99 726	99 730	99 734
994	99 739	99 743	99 747	99 752	99 756	99 760	99 765	99 769	99 774	99 778
995	99 782	99 787	99 791	99 795	99 800	99 804	99 808	99 813	99 817	99 822
996	99 826	99 830	99 835	99 839	99 843	99 848	99 852	99 856	99 861	99 865
997	99 870	99 874	99 878	99 883	99 887	99 891	99 896	99 900	99 904	99 909
998	99 913	99 917	99 922	99 926	99 930	99 935	99 939	99 944	99 948	99 952
999	99 957	99 961	99 965	99 970	99 974	99 978	99 983	99 987	99 991	99 996
1000	00 000	00 004	00 009	00 013	00 017	00 022	00 026	00 030	00 035	00 039
No.	**0**	**1**	**2**	**3**	**4**	**5**	**7**	**6**	**8**	**9**

APPENDIX B

Natural Sines, Cosines and Tangents

0°–14.9°

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
0	sin	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157
	cos	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.9999	0.9999	0.9999	0.9999
	tan	0.0000	0.0017	0.0035	0.0052	0.0070	0.0087	0.0105	0.0122	0.0140	0.0157
1	sin	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332
	cos	0.9998	0.9998	0.9998	0.9997	0.9997	0.9997	0.9996	0.9996	0.9995	0.9995
	tan	0.0175	0.0192	0.0209	0.0227	0.0244	0.0262	0.0279	0.0297	0.0314	0.0332
2	sin	0.0349	0.0366	0.0384	0.0401	0.0419	0.0436	0.0454	0.0471	0.0488	0.0506
	cos	0.9994	0.9993	0.9993	0.9992	0.9991	0.9990	0.9990	0.9989	0.9988	0.9987
	tan	0.0349	0.0367	0.0384	0.0402	0.0419	0.0437	0.0454	0.0472	0.0489	0.0507
3	sin	0.0523	0.0541	0.0558	0.0576	0.0593	0.0610	0.0628	0.0645	0.0663	0.0680
	cos	0.9986	0.9985	0.9984	0.9983	0.9982	0.9981	0.9980	0.9979	0.9978	0.9977
	tan	0.0524	0.0542	0.0559	0.0577	0.0594	0.0612	0.0629	0.0647	0.0664	0.0682
4	sin	0.0698	0.0715	0.0732	0.0750	0.0767	0.0785	0.0802	0.0819	0.0837	0.0854
	cos	0.9976	0.9974	0.9973	0.9972	0.9971	0.9969	0.9968	0.9966	0.9965	0.9963
	tan	0.0699	0.0717	0.0734	0.0752	0.0769	0.0787	0.0805	0.0822	0.0840	0.0857
5	sin	0.0872	0.0889	0.0906	0.0924	0.0941	0.0958	0.0976	0.0993	0.1011	0.1028
	cos	0.9962	0.9960	0.9959	0.9957	0.9956	0.9954	0.9952	0.9951	0.9949	0.9947
	tan	0.0875	0.0892	0.0910	0.0928	0.0945	0.0963	0.0981	0.0998	0.1016	0.1033
6	sin	0.1045	0.1063	0.1080	0.1097	0.1115	0.1132	0.1149	0.1167	0.1184	0.1201
	cos	0.9945	0.9943	0.9942	0.9940	0.9938	0.9936	0.9934	0.9932	0.9930	0.9928
	tan	0.1051	0.1069	0.1086	0.1104	0.1122	0.1139	0.1157	0.1175	0.1192	0.1210
7	sin	0.1219	0.1236	0.1253	0.1271	0.1288	0.1305	0.1323	0.1340	0.1357	0.1374
	cos	0.9925	0.9923	0.9921	0.9919	0.9917	0.9914	0.9912	0.9910	0.9907	0.9905
	tan	0.1228	0.1246	0.1263	0.1281	0.1299	0.1317	0.1334	0.1352	0.1370	0.1388
8	sin	0.1392	0.1409	0.1426	0.1444	0.1461	0.1478	0.1495	0.1513	0.1530	0.1547
	cos	0.9903	0.9900	0.9898	0.9895	0.9893	0.9890	0.9888	0.9885	0.9882	0.9880
	tan	0.1405	0.1423	0.1441	0.1459	0.1477	0.1495	0.1512	0.1530	0.1548	0.1566
9	sin	0.1564	0.1582	0.1599	0.1616	0.1633	0.1650	0.1668	0.1685	0.1702	0.1719
	cos	0.9877	0.9874	0.9871	0.9869	0.9866	0.9863	0.9860	0.9857	0.9854	0.9851
	tan	0.1584	0.1602	0.1620	0.1638	0.1655	0.1673	0.1691	0.1709	0.1727	0.1745
10	sin	0.1736	0.1754	0.1771	0.1788	0.1805	0.1822	0.1840	0.1857	0.1874	0.1891
	cos	0.9848	0.9845	0.9842	0.9839	0.9836	0.9833	0.9829	0.9826	0.9823	0.9820
	tan	0.1763	0.1781	0.1799	0.1817	0.1835	0.1853	0.1871	0.1890	0.1908	0.1926
11	sin	0.1908	0.1925	0.1942	0.1959	0.1977	0.1994	0.2011	0.2028	0.2045	0.2062
	cos	0.9816	0.9813	0.9810	0.9806	0.9803	0.9799	0.9796	0.9792	0.9789	0.9785
	tan	0.1944	0.1962	0.1980	0.1998	0.2016	0.2035	0.2053	0.2071	0.2089	0.2107
12	sin	0.2079	0.2096	0.2113	0.2130	0.2147	0.2164	0.2181	0.2198	0.2215	0.2232
	cos	0.9781	0.9778	0.9774	0.9770	0.9767	0.9763	0.9759	0.9755	0.9751	0.9748
	tan	0.2126	0.2144	0.2162	0.2180	0.2199	0.2217	0.2235	0.2254	0.2272	0.2290
13	sin	0.2250	2267	2284	0.2300	0.2318	0.2334	0.2351	0.2368	0.2385	0.2402
	cos	0.9744	0.9740	0.9736	0.9732	0.9728	0.9724	0.9720	0.9715	0.9711	0.9707
	tan	0.2309	0.2327	0.2345	0.2364	0.2382	0.2401	0.2419	0.2438	0.2456	0.2475
14	sin	0.2419	0.2436	0.2453	0.2470	0.2487	0.2504	0.2521	0.2538	0.2554	0.2571
	cos	0.9703	0.9699	0.9694	0.9690	0.9686	0.9681	0.9677	0.9673	0.9668	0.9664
	tan	0.2493	0.2512	0.2530	0.2549	0.2568	0.2586	0.2605	0.2623	0.2642	0.2661
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
15	sin	0.2588	0.2605	0.2622	0.2639	0.2656	0.2672	0.2689	0.2706	0.2723	0.2740
	cos	0.9659	0.9655	0.9650	0.9646	0.9641	0.9636	0.9632	0.9627	0.9622	0.9617
	tan	0.2679	0.2698	0.2717	0.2736	0.2754	0.2773	0.2792	0.2811	0.2830	0.2849
16	sin	0.2756	0.2773	0.2790	0.2807	0.2823	0.2840	0.2857	0.2874	0.2890	0.2907
	cos	0.9613	0.9608	0.9603	0.9598	0.9593	0.9588	0.9583	0.9578	0.9573	0.9568
	tan	0.2867	0.2886	0.2905	0.2924	0.2943	0.2962	0.2981	0.3000	0.3019	0.3038
17	sin	0.2924	0.2940	0.2957	0.2974	0.2990	0.3007	0.3024	0.3040	0.3057	0.3074
	cos	0.9563	0.9558	0.9553	0.9548	0.9542	0.9537	0.9532	0.9527	0.9521	0.9516
	tan	0.3057	0.3076	0.3096	0.3115	0.3134	0.3153	0.3172	0.3191	0.3211	0.3230
18	sin	0.3090	0.3107	0.3123	0.3140	0.3156	0.3173	0.3190	0.3206	0.3223	0.3230
	cos	0.9511	0.9505	0.9500	0.9494	0.9489	0.9483	0.9478	0.9472	0.9466	0.9461
	tan	0.3249	0.3269	0.3288	0.3307	0.3327	0.3346	0.3365	0.3385	0.3404	0.3424
19	sin	0.3256	0.3272	0.3289	0.3305	0.3322	0.3338	0.3355	0.3371	0.3387	0.3404
	cos	0.9455	0.9449	0.9444	0.9438	0.9432	0.9426	0.9421	0.9415	0.9409	0.9403
	tan	0.3443	0.3463	0.3482	0.3502	0.3522	0.3541	0.3561	0.3581	0.3600	0.3620
20	sin	0.3420	0.3437	0.3453	0.3469	0.3486	0.3502	0.3518	0.3535	0.3551	0.3567
	cos	0.9397	0.9391	0.9385	0.9379	0.9373	0.9367	0.9361	0.9354	0.9348	0.9342
	tan	0.3640	0.3659	0.3679	0.3699	0.3719	0.3739	0.3759	0.3779	0.3799	0.3819
21	sin	0.3584	0.3600	0.3616	0.3633	0.3649	0.3665	0.3681	0.3697	0.3714	0.3730
	cos	0.9336	0.9330	0.9323	0.9317	0.9311	0.9304	0.9298	0.9291	0.9285	0.9278
	tan	0.3839	0.3859	0.3879	0.3899	0.3919	0.3939	0.3959	0.3979	0.4000	0.4020
22	sin	0.3746	0.3762	0.3778	0.3795	0.3811	0.3827	0.3843	0.3859	0.3875	0.3891
	cos	0.9272	0.9265	0.9259	0.9252	0.9245	0.9239	0.9232	0.9225	0.9219	0.9212
	tan	0.4040	0.4061	0.4081	0.4101	0.4122	0.4142	0.4163	0.4183	0.4204	0.4224
23	sin	0.3907	0.3923	0.3939	0.3955	0.3971	0.3987	0.4003	0.4019	0.4035	0.4051
	cos	0.9205	0.9198	0.9191	0.9184	0.9178	0.9171	0.9164	0.9157	0.9150	0.9143
	tan	0.4245	0.4265	0.4286	0.4307	0.4327	0.4348	0.4369	0.4390	0.4411	0.4431
24	sin	0.4067	0.4083	0.4099	0.4115	0.4131	0.4147	0.4163	0.4179	0.4195	0.4210
	cos	0.9135	0.9128	0.9121	0.9114	0.9107	0.9100	0.9092	0.9085	0.9078	0.9070
	tan	0.4452	0.4473	0.4494	0.4515	0.4536	0.4557	0.4578	0.4599	0.4621	0.4642
25	sin	0.4226	0.4242	0.4258	0.4274	0.4289	0.4305	0.4321	0.4337	0.4352	0.4368
	cos	0.9063	0.9056	0.9048	0.9041	0.9033	0.9026	0.9018	0.9011	0.9003	0.8996
	tan	0.4663	0.4684	0.4706	0.4727	0.4748	0.4770	0.4791	0.4813	0.4834	0.4856
26	sin	0.4384	0.4399	0.4415	0.4431	0.4446	0.4462	0.4478	0.4493	0.4509	0.4524
	cos	0.8988	0.8980	0.8973	0.8965	0.8957	0.8949	0.8942	0.8934	0.8926	0.8918
	tan	0.4877	0.4899	0.4921	0.4942	0.4964	0.4986	0.5008	0.5029	0.5051	0.5073
27	sin	0.4540	0.4555	0.4571	0.4586	0.4602	0.4617	0.4633	0.4648	0.4664	0.4679
	cos	0.8910	0.8902	0.8894	0.8886	0.8878	0.8870	0.8862	0.8854	0.8846	0.8838
	tan	0.5095	0.5117	0.5139	0.5161	0.5184	0.5206	0.5228	0.5250	0.5272	0.5295
28	sin	0.4695	0.4710	0.4726	0.4741	0.4756	0.4772	0.4787	0.4802	0.4818	0.4833
	cos	0.8829	0.8821	0.8813	0.8805	0.8796	0.8788	0.8780	0.8771	0.8763	0.8755
	tan	0.5317	0.5340	0.5362	0.5384	0.5407	0.5430	0.5452	0.5475	0.5498	0.5520
29	sin	0.4848	0.4863	0.4879	0.4894	0.4909	0.4924	0.4939	0.4955	0.4970	0.4985
	cos	0.8746	0.8738	0.8729	0.8721	0.8712	0.8704	0.8695	0.8686	0.8678	0.8669
	tan	0.5543	0.5566	0.5589	0.5612	0.5635	0.5658	0.5681	0.5704	0.5727	0.5750
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6	0.7	0.8°	0.9°
30	sin	0.5000	0.5015	0.5030	0.5045	0.5060	0.5075	0.5090	0.5105	0.5120	0.5135
	cos	0.8660	0.8652	0.8643	0.8634	0.8625	0.8616	0.8607	0.8599	0.8590	0.8581
	tan	0.5774	0.5797	0.5820	0.5844	0.5867	0.5890	0.5914	0.5938	0.5961	0.5985
31	sin	0.5150	0.5165	0.5180	0.5195	0.5210	0.5225	0.5240	0.5255	0.5270	0.5284
	cos	0.8572	0.8563	0.8554	0.8545	0.8536	0.8526	0.8517	0.8508	0.8499	0.8490
	tan	0.6009	0.6032	0.6056	0.6080	0.6104	0.6128	0.6152	0.6176	0.6200	0.6224
32	sin	0.5299	0.5314	0.5329	0.5344	0.5358	0.5373	0.5388	0.5402	0.5417	0.5432
	cos	0.8480	0.8471	0.8462	0.8453	0.8443	0.8434	0.8425	0.8415	0.8406	0.8396
	tan	0.6249	0.6273	0.6297	0.6322	0.6346	0.6371	0.6395	0.6420	0.6445	0.6469
33	sin	0.5446	0.5461	0.5476	0.5490	0.5505	0.5519	0.5534	0.5548	0.5563	0.5577
	cos	0.8387	0.8377	0.8368	0.8358	0.8348	0.8339	0.8329	0.8320	0.8310	0.8300
	tan	0.6494	0.6519	0.6544	0.6569	0.6594	0.6619	0.6644	0.6669	0.6694	0.6720
34	sin	0.5592	0.5606	0.5621	0.5635	0.5650	0.5664	0.5678	0.5693	0.5707	0.5721
	cos	0.8290	0.8281	0.8271	0.8261	0.8251	0.8241	0.8231	0.8221	0.8211	0.8202
	tan	0.6745	0.6771	0.6796	0.6822	0.6847	0.6873	0.6899	0.6924	0.6950	0.6976
35	sin	0.5736	0.5750	0.5764	0.5779	0.5793	0.5807	0.5821	0.5835	0.5850	0.5864
	cos	0.8192	0.8181	0.8171	0.8161	0.8151	0.8141	0.8131	0.8121	0.8111	0.8100
	tan	0.7002	0.7028	0.7054	0.7080	0.7107	0.7133	0.7159	0.7186	0.7212	0.7239
36	sin	0.5878	0.5892	0.5906	0.5920	0.5934	0.5948	0.5962	0.5976	0.5990	0.6004
	cos	0.8090	0.8080	0.8070	0.8059	0.8049	0.8039	0.8028	0.8018	0.8007	0.7997
	tan	0.7265	0.7292	0.7319	0.7346	0.7373	0.7400	0.7427	0.7454	0.7481	0.7508
37	sin	0.6018	0.6032	0.6046	0.6060	0.6074	0.6088	0.6101	0.6115	0.6129	0.6143
	cos	0.7986	0.7976	0.7965	0.7955	0.7944	0.7934	0.7923	0.7912	0.7902	0.7891
	tan	0.7536	0.7563	0.7590	0.7618	0.7646	0.7673	0.7701	0.7729	0.7757	0.7785
38	sin	0.6157	0.6170	0.6184	0.6198	0.6211	0.6225	0.6239	0.6252	0.6266	0.6280
	cos	0.7880	0.7869	0.7859	0.7848	0.7837	0.7826	0.7815	0.7804	0.7793	0.7782
	tan	0.7813	0.7841	0.7869	0.7898	0.7926	0.7954	0.7983	0.8012	0.8040	0.8069
39	sin	0.6293	0.6307	0.6320	0.6334	0.6347	0.6361	0.6374	0.6388	0.6401	0.6414
	cos	0.7771	0.7760	0.7749	0.7738	0.7727	0.7716	0.7705	0.7694	0.7683	0.7672
	tan	0.8098	0.8127	0.8156	0.8185	0.8214	0.8243	0.8273	0.8302	0.8332	0.8361
40	sin	0.6428	0.6441	0.6455	0.6468	0.6481	0.6491 0.6494	0.6508	0.6521	0.6534	0.6547
	cos	0.7660	0.7649	0.7638	0.7627	0.7615	0.7604	0.7593	0.7581	0.7570	0.7559
	tan	0.8391	0.8421	0.8451	0.8481	0.8511	0.8541	0.8571	0.8601	0.8632	0.8662
41	sin	0.6561	0.6574	0.6587	0.6600	0.6613	0.6626	0.6639	0.6652	0.6665	0.6678
	cos	0.7547	0.7536	0.7524	0.7513	0.7501	0.7490	0.7478	0.7466	0.7455	0.7443
	tan	0.8693	0.8724	0.8754	0.8785	0.8816	0.8847	0.8878	0.8910	0.8941	0.8972
42	sin	0.6691	0.6704	0.6717	0.6730	0.6743	0.6756	0.6769	0.6782	0.6794	0.6807
	cos	0.7431	0.7420	0.7408	0.7396	0.7385	0.7373	0.7361	0.7349	0.7337	0.7325
	tan	0.9004	0.9036	0.9067	0.9099	0.9131	0.9163	0.9195	0.9228	0.9260	0.9293
43	sin	0.6820	0.6833	0.6845	0.6858	0.6871	0.6884	0.6896	0.6909	0.6921	0.6934
	cos	0.7314	0.7302	0.7290	0.7278	0.7266	0.7254	0.7242	0.7230	0.7218	0.7206
	tan	0.9325	0.9358	0.9391	0.9424	0.9457	0.9490	0.9523	0.9556	0.9590	0.9623
44	sin	0.6947	0.6959	0.6972	0.6984	0.6997	0.7009	0.7022	0.7034	0.7046	0.7059
	cos	0.7193	0.7181	0.7169	0.7157	0.7145	0.7133	0.7120	0.7108	0.7096	0.7083
	tan	0.9657	0.9691	0.9725	0.9759	0.9793	0.9827	0.9861	0.9896	0.9930	0.9965
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
45	sin	0.7071	0.7083	0.7096	0.7108	0.7120	0.7133	0.7145	0.7157	0.7169	0.7181
	cos	0.7071	0.7059	0.7046	0.7034	0.7022	0.7009	0.6997	0.6984	0.6972	0.6959
	tan	1.0000	1.0035	1.0070	1.0105	1.0141	1.0176	1.0212	1.0247	1.0283	1.0319
46	sin	0.7193	0.7206	0.7218	0.7230	0.7242	0.7254	0.7266	0.7278	0.7290	0.7302
	cos	0.6947	0.6934	0.6921	0.6909	0.6896	0.6884	0.6871	0.6858	0.6845	0.6833
	tan	1.0355	1.0392	1.0428	1.0464	1.0501	1.0538	1.0575	1.0612	1.0649	1.0686
47	sin	0.7314	0.7325	0.7337	0.7349	0.7361	0.7373	0.7385	0.7396	0.7408	0.7420
	cos	0.6820	0.6807	0.6794	0.6782	0.6769	0.6756	0.6743	0.6730	0.6717	0.6704
	tan	1.0724	1.0761	1.0799	1.0837	1.0875	1.0913	1.0951	1.0990	1.1028	1.1067
48	sin	0.7431	0.7443	0.7455	0.7466	0.7478	0.7490	0.7501	0.7513	0.7524	0.7536
	cos	0.6691	0.6678	0.6665	0.6652	0.6639	0.6626	0.6613	0.6600	0.6587	0.6574
	tan	1.1106	1.1145	1.1184	1.1224	1.1263	1.1303	1.1343	1.1383	1.1423	1.1463
49	sin	0.7547	0.7559	0.7570	0.7581	0.7593	0.7604	0.7615	0.7627	0.7638	0.7649
	cos	0.6561	0.6547	0.6534	0.6521	0.6508	0.6494	0.6481	0.6468	0.6455	0.6441
	tan	1.1504	1.1544	1.1585	1.1626	1.1667	1.1708	1.1750	1.1792	1.1833	1.1875
50	sin	0.7660	0.7672	0.7683	0.7694	0.7705	0.7716	0.7727	0.7738	0.7749	0.7760
	cos	0.6428	0.6414	0.6401	0.6388	0.6374	0.6361	0.6347	0.6334	0.6320	0.6307
	tan	1.1918	1.1960	1.2002	1.2045	1.2088	1.2131	1.2174	1.2218	1.2261	1.2305
51	sin	0.7771	0.7782	0.7793	0.7804	0.7815	0.7826	0.7837	0.7848	0.7859	0.7869
	cos	0.6293	0.6280	0.6266	0.6252	0.6239	0.6225	0.6211	0.6198	0.6184	0.6170
	tan	1.2349	1.2393	1.2437	1.2482	1.2527	1.2572	1.2617	1.2662	1.2708	1.2753
52	sin	0.7880	0.7891	0.7902	0.7912	0.7923	0.7934	0.7944	0.7955	0.7965	0.7976
	cos	0.6157	0.6143	0.6129	0.6115	0.6101	0.6088	0.6074	0.6060	0.6046	0.6032
	tan	1.2799	1.2846	1.2892	1.2938	1.2985	1.3032	1.3079	1.3127	1.3175	1.3222
53	sin	0.7986	0.7997	0.8007	0.8018	0.8028	0.8039	0.8049	0.8059	0.8070	0.8080
	cos	0.6018	0.6004	0.5990	0.5976	0.5962	0.5948	0.5934	0.5920	0.5906	0.5892
	tan	1.3270	1.3319	1.3367	1.3416	1.3465	1.3514	1.3564	1.3613	1.3663	1.3713
54	sin	0.8090	0.8100	0.8111	0.8121	0.8131	0.8141	0.8151	0.8161	0.8171	0.8181
	cos	0.5878	0.5864	0.5850	0.5835	0.5821	0.5807	0.5793	0.5779	0.5764	0.5750
	tan	1.3764	1.3814	1.3865	1.3916	1.3968	1.4019	1.4071	1.4124	1.4176	1.4229
55	sin	0.8192	0.8202	0.8211	0.8221	0.8231	0.8241	0.8251	0.8261	0.8271	0.8281
	cos	0.5736	0.5721	0.5707	0.5693	0.5678	0.5664	0.5650	0.5635	0.5621	0.5606
	tan	1.4281	1.4335	1.4388	1.4442	1.4496	1.4550	1.4605	1.4659	1.4715	1.4770
56	sin	0.8290	0.8300	0.8310	0.8320	0.8329	0.8339	0.8348	0.8358	0.8368	0.8377
	cos	0.5592	0.5577	0.5563	0.5548	0.5534	0.5519	0.5505	0.5490	0.5476	0.5461
	tan	1.4826	1.4882	1.4938	1.4994	1.5051	1.5108	1.5166	1.5224	1.5282	1.5340
57	sin	0.8387	0.8396	0.8406	0.8415	0.8425	0.8434	0.8443	0.8453	0.8462	0.8471
	cos	0.5446	0.5432	0.5417	0.5402	0.5388	0.5373	0.5358	0.5344	0.5329	0.5314
	tan	1.5399	1.5458	1.5517	1.5577	1.5637	1.5697	1.5757	1.5818	1.5880	1.5941
58	sin	0.8480	0.8490	0.8499	0.8508	0.8517	0.8526	0.8536	0.8545	0.8554	0.8563
	cos	0.5299	0.5284	0.5270	0.5255	0.5240	0.5225	0.5210	0.5195	0.5180	0.5165
	tan	1.6003	1.6066	1.6128	1.6191	1.6255	1.6319	1.6383	1.6447	1.6512	1.6577
59	sin	0.8572	0.8581	0.8590	0.8599	0.8607	0.8616	0.8625	0.8634	0.8643	0.8652
	cos	0.5150	0.5135	0.5120	0.5105	0.5090	0.5075	0.5060	0.5045	0.5030	0.5015
	tan	1.6643	1.6709	1.6775	1.6842	1.6909	1.6977	1.7045	1.7113	1.7182	1.7251
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
60	sin	0.8660	0.8669	0.8678	0.8686	0.8695	0.8704	0.8712	0.8721	0.8729	0.8738
	cos	0.5000	0.4985	0.4970	0.4955	0.4939	0.4924	0.4909	0.4894	0.4879	0.4863
	tan	1.7321	1.7391	1.7461	1.7532	1.7603	1.7675	1.7747	1.7820	1.7893	1.7966
61	sin	0.8746	0.8755	0.8763	0.8771	0.8780	0.8788	0.8796	0.8805	0.8813	0.8821
	cos	0.4848	0.4833	0.4818	0.4802	0.4787	0.4772	0.4756	0.4741	0.4726	0.4710
	tan	1.8040	1.8115	1.8190	1.8265	1.8341	1.8418	1.8495	1.8572	1.8650	1.8728
62	sin	0.8829	0.8838	0.8846	0.8854	0.8862	0.8870	0.8878	0.8886	0.8894	0.8902
	cos	0.4695	0.4679	0.4664	0.4648	0.4633	0.4617	0.4602	0.4586	0.4571	0.4555
	tan	1.8807	1.8887	1.8967	1.9047	1.9128	1.9210	1.9292	1.9375	1.9458	1.9542
63	sin	0.8910	0.8918	0.8926	0.8934	0.8942	0.8949	0.8957	0.8965	0.8973	0.8980
	cos	0.4540	0.4524	0.4509	0.4493	0.4478	0.4462	0.4446	0.4431	0.4415	0.4399
	tan	1.9626	1.9711	1.9797	1.9883	1.9970	2.0057	2.0145	2.0233	2.0323	2.0413
64	sin	0.8988	0.8996	0.9003	0.9011	0.9018	0.9026	0.9033	0.9041	0.9048	0.9056
	cos	0.4384	0.4368	0.4352	0.4337	0.4321	0.4305	0.4289	0.4274	0.4258	0.4242
	tan	2.0503	2.0594	2.0686	2.0778	2.0872	2.0965	2.1060	2.1155	2.1251	2.1348
65	sin	0.9063	0.9070	0.9078	0.9085	0.9092	0.9100	0.9107	0.9114	0.9121	0.9128
	cos	0.4226	0.4210	0.4195	0.4179	0.4163	0.4147	0.4131	0.4115	0.4099	0.4083
	tan	2.1445	2.1543	2.1642	2.1742	2.1842	2.1943	2.2045	2.2148	2.2251	2.2355
66	sin	0.9135	0.9143	0.9150	0.9157	0.9164	0.9171	0.9178	0.9184	0.9191	0.9198
	cos	0.4067	0.4051	0.4035	0.4019	0.4003	0.3987	0.3971	0.3955	0.3939	0.3923
	tan	2.2460	2.2566	2.2673	2.2781	2.2889	2.2998	2.3109	2.3220	2.3332	2.3445
67	sin	0.9205	0.9212	0.9219	0.9225	0.9232	0.9239	0.9245	0.9252	0.9259	0.9265
	cos	0.3907	0.3891	0.3875	0.3859	0.3843	0.3827	0.3811	0.3795	0.3778	0.3762
	tan	2.3559	2.3673	2.3789	2.3906	2.4023	2.4142	2.4262	2.4383	2.4504	2.4627
68	sin	0.9272	0.9278	0.9285	0.9291	0.9298	0.9304	0.9311	0.9317	0.9323	0.9330
	cos	0.3746	0.3730	0.3714	0.3697	0.3681	0.3665	0.3649	0.3633	0.3616	0.3600
	tan	2.4751	2.4876	2.5002	2.5129	2.5257	2.5386	2.5517	2.5649	2.5782	2.5916
69	sin	0.9336	0.9342	0.9348	0.9354	0.9361	0.9367	0.9373	0.9379	0.9385	0.9391
	cos	0.3584	0.3567	0.3551	0.3535	0.3518	0.3502	0.3486	0.3469	0.3453	0.3437
	tan	2.6051	2.6187	2.6325	2.6464	2.6605	2.6746	2.6889	2.7034	2.7179	2.7326
70	sin	0.9397	0.9403	0.9409	0.9415	0.9421	0.9426	0.9432	0.9438	0.9444	0.9449
	cos	0.3420	0.3404	0.3387	0.3371	0.3355	0.3338	0.3322	0.3305	0.3289	0.3272
	tan	2.7475	2.7625	2.7776	2.7929	2.8083	2.8239	2.8397	2.8556	2.8716	2.8878
71	sin	0.9455	0.9461	0.9466	0.9472	0.9478	0.9483	0.9489	0.9494	0.9500	0.9505
	cos	0.3256	0.3239	0.3223	0.3206	0.3190	0.3173	0.3156	0.3140	0.3123	0.3107
	tan	2.9042	2.9208	2.9375	2.9544	2.9714	2.9887	3.0061	3.0237	3.0415	3.0595
72	sin	0.9511	0.9516	0.9521	0.9527	0.9532	0.9537	0.9542	0.9548	0.9553	0.9558
	cos	0.3090	0.3074	0.3057	0.3040	0.3024	0.3007	0.2990	0.2974	0.2957	0.2940
	tan	3.0777	3.0961	3.1146	3.1334	3.1524	3.1716	3.1910	3.2106	3.2305	3.2506
73	sin	0.9563	0.9568	0.9573	0.9578	0.9583	0.9588	0.9593	0.9598	0.9603	0.9608
	cos	0.2924	0.2907	0.2890	0.2874	0.2857	0.2840	0.2823	0.2807	0.2790	0.2773
	tan	3.2709	3.2914	3.3122	3.3332	3.3544	3.3759	3.3977	3.4197	3.4420	3.4646
74	sin	0.9613	0.9617	0.9622	0.9627	0.9632	0.9636	0.9641	0.9646	0.9650	0.9655
	cos	0.2756	0.2740	0.2723	0.2706	0.2689	0.2672	0.2656	0.2639	0.2622	0.2605
	tan	3.4874	3.5105	3.5339	3.5576	3.5816	3.6059	3.6305	3.6554	3.6806	3.7062
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Degs.	Function	0.0°	0.1°	0.2°	0.3°	0.4°	0.5°	0.6°	0.7°	0.8°	0.9°
75	sin	0.9659	0.9664	0.9668	0.9673	0.9677	0.9681	0.9686	0.9690	0.9694	0.9699
	cos	0.2588	0.2571	0.2554	0.2538	0.2521	0.2504	0.2487	0.2470	0.2453	0.2436
	tan	3.7321	3.7583	3.7848	3.8118	3.8391	3.8667	3.8947	3.9232	3.9520	3.9812
76	sin	0.9703	0.9707	0.9711	0.9715	0.9720	0.9724	0.9728	0.9732	0.9736	0.9740
	cos	0.2419	0.2402	0.2385	0.2368	0.2351	0.2334	0.2317	0.2300	0.2284	0.2267
	tan	4.0108	4.0408	4.0713	4.1022	4.1335	4.1653	4.1976	4.2303	4.2635	4.2972
77	sin	0.9744	0.9748	0.9751	0.9755	0.9759	0.9763	0.9767	0.9770	0.9774	0.9778
	cos	0.2250	0.2232	0.2215	0.2198	0.2181	0.2164	0.2147	0.2130	0.2113	0.2096
	tan	4.3315	4.3662	4.4015	4.4374	4.4737	4.5107	4.5483	4.5864	4.6252	4.6646
78	sin	0.9781	0.9785	0.9789	0.9792	0.9796	0.9799	0.9803	0.9806	0.9810	0.9813
	cos	0.2079	0.2062	0.2045	0.2028	0.2011	0.1994	0.1977	0.1959	0.1942	0.1925
	tan	4.7046	4.7453	4.7867	4.8288	4.8716	4.9152	4.9594	5.0045	5.0504	5.0970
79	sin	0.9816	0.9820	0.9823	0.9826	0.9829	0.9833	0.9836	0.9839	0.9842	0.9845
	cos	0.1908	0.1891	0.1874	0.1857	0.1840	0.1822	0.1805	0.1788	0.1771	0.1754
	tan	5.1446	5.1929	5.2422	5.2924	5.3435	5.3955	5.4486	5.5026	5.5578	5.6140
80	sin	0.9848	0.9851	0.9854	0.9857	0.9860	0.9863	0.9866	0.9869	0.9871	0.9874
	cos	0.1736	0.1719	0.1702	0.1685	0.1668	0.1650	0.1633	0.1616	0.1599	0.1582
	tan	5.6713	5.7297	5.7894	5.8502	5.9124	5.9758	6.0405	6.1066	6.1742	6.2432
81	sin	0.9877	0.9880	0.9882	0.9885	0.9888	0.9890	0.9893	0.9895	0.9898	0.9900
	cos	0.1564	0.1547	0.1530	0.1513	0.1495	0.1478	0.1461	0.1444	0.1426	0.1409
	tan	6.3138	6.3859	6.4596	6.5350	6.6122	6.6912	6.7720	6.8548	6.9395	7.0264
82	sin	0.9903	0.9905	0.9907	0.9910	0.9912	0.9914	0.9917	0.9919	0.9921	0.9923
	cos	0.1392	0.1374	0.1357	0.1340	0.1323	0.1305	0.1288	0.1271	0.1253	0.1236
	tan	7.1154	7.2066	7.3002	7.3962	7.4947	7.5958	7.6996	7.8062	7.9158	8.0285
83	sin	0.9925	0.9928	0.9930	0.9932	0.9934	0.9936	0.9938	0.9940	0.9942	0.9943
	cos	0.1219	0.1201	0.1184	0.1167	0.1149	0.1132	0.1115	0.1097	0.1080	0.1063
	tan	8.1443	8.2636	8.3863	8.5126	8.6427	8.7769	8.9152	9.0579	9.2052	9.3572
84	sin	0.9945	0.9947	0.9949	0.9951	0.9952	0.9954	0.9956	0.9957	0.9959	0.9960
	cos	0.1045	0.1028	0.1011	0.0993	0.0976	0.0958	0.0941	0.0924	0.0906	0.0889
	tan	9.5144	9.6768	9.8448	10.02	10.20	10.39	10.58	10.78	10.99	11.20
85	sin	0.9962	0.9963	0.9965	0.9966	0.9968	0.9969	0.9971	0.9972	0.9973	0.9974
	cos	0.0872	0.0854	0.0837	0.0819	0.0802	0.0785	0.0767	0.0750	0.0732	0.0715
	tan	11.43	11.66	11.91	12.16	12.43	12.71	13.00	13.30	13.62	13.95
86	sin	0.9976	0.9977	0.9978	0.9979	0.9980	0.9981	0.9982	0.9983	0.9984	0.9985
	cos	0.0698	0.0680	0.0663	0.0645	0.0628	0.0610	0.0593	0.0576	0.0558	0.0541
	tan	14.30	14.67	15.06	15.46	15.89	16.35	16.83	17.34	17.89	18.46
87	sin	0.9986	0.9987	0.9988	0.9989	0.9990	0.9990	0.9991	0.9992	0.9993	0.9993
	cos	0.0523	0.0506	0.0488	0.0471	0.0454	0.0436	0.0419	0.0401	0.0384	0.0366
	tan	19.08	19.74	20.45	21.20	22.02	22.90	23.86	24.90	26.03	27.27
88	sin	0.9994	0.9995	0.9995	0.9996	0.9996	0.9997	0.9997	0.9997	0.9998	0.9998
	cos	0.0349	0.0332	0.0314	0.0297	0.0279	0.0262	0.0244	0.0227	0.0209	0.0192
	tan	28.64	30.14	31.82	33.69	35.80	38.19	40.92	44.07	47.74	52.08
89	sin	0.9998	0.9999	0.9999	0.9999	0.9999	1.000	1.000	1.000	1.000	1.000
	cos	0.0175	0.0157	0.0140	0.0122	0.0105	0.0087	0.0070	0.0052	0.0035	0.0017
	tan	57.29	63.66	71.62	81.85	95.49	114.6	143.2	191.0	286.5	573.0
Degs.	Function	0′	6′	12′	18′	24′	30′	36′	42′	48′	54′

Answers for Exercises

CHAPTER 1

Reference:

600 – 1. 3.24452.
2. 1.96685.
3. 0.20493.
4. 2.92397.

601 – 1. 32,560.0.
2. 4.058.
3. 0.01668.
4. 1,002.0.

602 – 1. 9.393.
2. 8.288.
3. 149.9.
4. 8.629.
5. 4.681.
6. 3.583×10^7.

603 – 1. A 25-percent increase.
2. The decibel is based upon the response of the human ear to sound levels. The human ear responds logarithmically to sound; therefore, the decibel is also a logarithimic function.
3. Negative decibels are indicative of a ratio less than one, a decimal fraction.
4. The attenuator reduces the input power so that the ratio of output power to input power is less than one, a decimal fraction indicating loss.
5. A dBm is equal to one milliwatt.
6. $$\text{dB} = 10 \log \frac{\text{power large}}{\text{power small}}$$
$$7.2 = \log \frac{15 \text{ mW}}{X}$$
$$\text{antilog } 0.72 = \frac{15 \text{ mW}}{X}$$
$$5.248 = \frac{15 \text{ mW}}{X}$$
$$X = \frac{15 \text{ mW}}{5.248}$$
$$X = 2.858 \text{ mW} = \text{power out}$$
7. $$\text{db} = 10 \log \frac{\text{power large}}{\text{power small}}$$
$$= 10 \log \frac{656 \text{ mW}}{3.2 \text{ mW}}$$
$$= 10 \log 205.0$$
$$= 10 \times 2.31175$$
$$\text{dB} = 23.1175$$
8. $$\text{dBm} = 10 \log \frac{\text{P large}}{1 \text{ mW}}$$
$$-\text{dBm} = 10 \log \frac{1 \text{ mW}}{5 \text{ mW}}$$
$$= 10 \log 0.2 \times 10^3$$
$$= 10 \log 2\ 0 \times 10^2$$
$$= 10 \times 2.30103$$
$$-\text{dBm} = 23.0103$$
9. The output from the attenuator is 9 dB shown from the input, which is −6 dBm, or −15 dBm. Using the formula:
$$-\text{dBm} = 10 \log \frac{1 \text{ mW}}{X}$$
$$15 = 10 \log \frac{1 \text{ mW}}{X}$$
$$1.5 = \log \frac{1 \text{ mW}}{X} \quad (\text{Antilog } 1.5 = 31.62)$$
$$31.62 = \frac{1 \text{ mW}}{X}$$
$$31.62X = 1 \text{ mW}$$
$$X = 31.62 \mu\text{w or } -15 \text{ dBm}.$$
Another, simpler, though less accurate method of solving this problem is to halve the quantity, 1 mW, 5 times, recalling that 3 dB of attenuation reduces the power by half. This solution yields a value of 31.25 W, not exact, but a close approximation of the true value.
10. This circuit resolves to an amplifier having a gain of 10 dB and an input of −23 dBm. The output then is −13 dBm. Using the formula:
$$-\text{dBm} = 10 \log \frac{1 \text{ mW}}{X}$$
$$13 \text{ dBm} = 10 \log \frac{1 \text{ mW}}{X}$$
$$1.3 = \log \frac{1 \text{ mW}}{X}$$
$$19.95 = \frac{1 \text{ mW}}{X}$$
$$X = 50.12 \ \mu\text{w}.$$

604 – 1. Characteristic impedance of a transmission line is determined by the spacing of the conductors and the dielectric material separating the conductors. These factors control the series resistance, series inductance, and shunt capacitance for each unit length of transmission line.
2. The transmission line assumes its characteristic impedance after a number of sections of lumped constants are added to line. This means that a transmission line has to be long for it to have the characteristic impedance reflected to the generator.
3. The characteristic impedance will change due to the capacitance and inductance of the line.
4. Series distributed resistance.

605 – 1. Wavelength can be determined by dividing the speed of light in meters per second (or miles, feet, or other measure) by the frequency in Hz.
2. The wavelength of a specific frequency in free space differs from that of it along a transmission line because the transmission line attenuates the transmitted signal. The relationship between the two is determined by the division of the wavelength of a frequency on the line by the wavelength of the same frequency in free space.
3. The wavelength of the signal is 30 meters.
$$\lambda \text{ (meters)} = \frac{300 \times 10^6}{10 \times 10^6}$$
$$\lambda = 30 \text{ meters}$$
4. The frequency is 15 GHz.
$$\lambda \text{ (centimeters)} = \frac{300 \times 10^8}{f}$$
$$f = \frac{300 \times 10^8}{f}$$
$$f = \frac{300 \times 10^8}{\lambda}$$
$$f = \frac{300 \times 10^8}{2}$$
$$f = \frac{150 \times 10^8}{2}$$
$$f = 15 \times 10^9 \text{ or } 15 \text{ GHz}$$

606 – 1. Standing waves are produced by reflections caused by the termination of the line. The termination must be equal to the characteristic impedance for no reflections to occur. Any other termination which does not absorb or dissipate all of the power produces some reflection.
2. Whenever no standing waves are present on the transmission line, the line is said to be *flat* or *nonresonant*.
3. A transmission line terminated in a short produces a voltage minimum at the termination, and the minimum repeats every half wavelength from the termination.
4. The VSWR measured on a transmission line is a representation of the amount of power absorbed or dissipated by the load. When the termination is equal to Zo, no VSWR should be measured. An increasing VSWR is indicative of less and less power being absorbed by the load. When the load is terminated in a short or open and you get 100 percent reflection, the VSWR is essentially infinite.
5. Incident wave, reflected wave, and standing wave. The incident wave originates at the input to the line and travels toward the termination. The reflected wave starts at the termination and travels toward the line input. The standing wave occurs as a result of resonant line reactance and does not travel in either direction.
6. There would be no reflected wave when the line is terminated by a resistance equal to the characteristic impedance of the line.

607 – 1. With a termination of a short or open, the VSWR is infinite, and the gamma of the line is 1.
2. The actual power can be determined by computing the reflected power from the following formula:

$$\text{Percentage of reflected power} = 100 \left(\frac{1.2-1}{1.2+1}\right)^2$$

$$= 100 \left(\frac{0.2}{2.2}\right)^2$$

$$= 100\ (0.09)^2$$

$$= 0.8\%$$

The reflected power is equal to 0.8 percent of the total power: therefore, 3.6 mW measured at the termination is equal to 99.2 percent of the total power. A ratio and proportion can then be used to determine the generator power output:

$$\frac{100}{99.2} = \frac{P^t}{3.6}$$

By solving the ratio and proportion, the total power output of the generator can be computed.
3. The reflection coefficient represents the ratio of the reflected wave to the incident wave.
4. Zo = 150 ohms
At resonance Zo = R_L

$$\Gamma = \frac{Zo - R_L}{Zo + R_L}$$

$$\Gamma = \frac{150 - 150}{150 + 150}$$

$$\Gamma = \frac{0}{300}$$

$$\Gamma = 0$$

608 – 1. A normalized value of voltage or current is either the sine or cosine of the generator's angular displacement, depending upon the phase relationship of voltage and current produced by the generator, while the actual value of voltage or current is the sine or cosine value multiplied by the peak value.
2. The normalized impedance is equal to the tangent function of the generator's angular displacement when the voltage and current are 90° out of phase.
3. Inductive vector characteristics result from a phase difference of 0° to 90° phase difference between voltage and current.
4. From a trigonometric table tangent of 34° = 0.674. Using the formula Z = Zo (0.0674), we find that Z = 34.048 ohms. Starting from the load, the line is shorted; therefore, impedance is minimum and increases toward the generator. An increasing impedance from the load is inductive. The impedance, therefore, is 34.048 ohms XL.
5. The normalized capacitive reactance at 180° is zero.
6. The normalized impedance will always equal one when the incident and current waves are in phase.
7. Starting from the load and going towards the generator, a decreasing impedance is identified as a capacitive reactance.

609 – 1. The field intensity of the forward wave is minimum at the ferrite slab, while the field intensity of the reverse wave is maximum. The ferrite slab has a resistive coating, which absorbs most of the energy because of the high intensity.
2. The input and output connections of a ferrite isolator are marked and should be connected accordingly. Also, you should not strike the magnet as this causes it to lose some of its strength. Because of the magnetic field, no equipment that is affected by a magnetic field should be brought next to the ferrite isolator.
3. The waveguide isolator prevents reflected energy from traveling backward in the line, thereby protecting circuit components.

610 – 1. The klystron is known as a velocity-modulated tube because it causes the emitte electrons to accelerate or decelerate at different rates (varying velocities).
2. The catcher grids absorb the energy from the electron bunches.
3. The frequencies are the same.
4. The control grid focuses the electron flow into a sharp beam.
5. The reflex klystron is more widely used because of the difficulty encountered in the mechanical tuning of the two cavities in the double-cavity klystron.
6. The double-cavity klystron has a greater power output.
7. The electrons hit the collector plate and return to the cathode through an external circuit.

611 – 1. The double-cavity klystron has a plate which is called a *collector plate*. Because the voltage applied to the plate is positive with respect to the grids, electrons that pass through the cavity grids are attracted and collected by the plate. The reflex klystron has a plate which is called a *reflector* or *repeller plate*. Because the voltage applied to the plate is negative with respect to the grids, electrons that pass through the cavity grids are repelled by the plate.
2. As electrons travel toward the cavity grid, they all travel at the same speed. An AC voltage on the grid causes the electrons to either speed up or slow down, depending on the voltage amplitude at the time the electrons reach the grid. During the positive part of the cycle, electrons are accelerated, at cycle zero no acceleration takes place, and during the negative part of the cycle the electrons are decelerated. The result is varying amounts of travel and velocity at the AC rate. These electrons continue on toward the repeller plate until they are turned back toward the cavity where they arrive in bunches.
3. The electron bunches must arrive at grids when the grids are at a positive maximum.
4. No. The electrons movement is decelerated on the positive portion of the AC voltage cycle and accelerated on the negative portion of the cycle after burning.

612 – 1. The reflex klystron frequency can be changed either by mechanically varying the resonant cavity size or electronically by varying the repeller-plate voltage.
2. The electronic tuning range is the range of frequencies over which the power output exceeds 50 percent of the maximum output of the mode.
3. Variations of repeller-plate voltage can change the frequency, mode of operation, and level of energy output.
4. As the voltage is made more negative, the power output increases to maximum (at the resonant frequency) and then drops to zero again as oscillations stop. The frequency of oscillation during the same time goes from below the resonant frequency to above the resonant frequency.

5. The electrons travel a shorter distance during a lower mode allowing the bunches to form more rapidly with less overbunching.

613 – 1. Varying signals, such as sinusoidal voltages, etc, applied to the repeller or beam of the klystron will cause unwanted changes in the output frequency. These changes are largely uncontrolled, and their results unpredictable.
2. The effects of finite rise and decay times are much the same as that of any other analog signal—unwanted frequency variations.
3. Overshoots on the modulating pulse cause sudden unpredictable frequency modulation of the klystron output.

614 – 1. The magnet surrounding the helix concentrates and focuses the emitted electrons from the cathode into a thin, pinlike beam.
2. The helix receives the CW, RF signal input from the type "N" connector.
3. The interaction between electric fields of the electron bunches and the helix signal, aiding each other, make amplification possible.
4. The original CW, RF signal, which was applied to the helix, was reduced to nearly zero by the attenuators placed in the center of the helix. The output signal is a result of the electron bunches, unaffected by the attenuators, inducing a new helix signal onto the helix turns, with the accompanying amplification.
5. The TWT is an amplifier requiring an input signal in order to have an output signal.
6. The focusing occurs as a result of a magnetic field around the tube.
7. The two signals are in-phase and in same place, but the power output is greater.

615 – 1. The application of 115 volts to K2 (or its removal) is involved in each of the TWT protection circuits. In the time delay protection circuit, power is prevented from energizing K2 by the time delay relay K3 for a 2-minute period. In the overcurrent or overtemperature function, power to K2 is removed by either K1 (overcurrent condition) or TS1 (overtemperature condition).
2. Power is restored after an overcurrent condition by depressing the reset knob. Power is restored for an overtemperature condition automatically after the TWT cools down.

616 – 1. The capacitors, in parallel with the diodes of the high-voltage power, supplies suppress transients in the circuit.
2. A sample of the helix supply voltage is compared to a regulator reference voltage in the differential amplifier. Any difference is amplified, developed across R29, and applied to the grid of V1 (the helix voltage regulator tube) to control the helix voltage.

617 – 1. The frequency-selective feedback and amplification process which results from the interaction of the various electric fields within the BWO determines the operating frequency of the BWO.
2. The beam of the TWT is a pinlike focused beam; the electron beam in the BWO is a hollow, tubelike beam which lies close to the helix turns.
3. The RF energy of the BWO moves and builds up in a direction opposite to the electron movement through the tube. The output is taken out at the gun end.
4. Because the velocity of the electron beam is the primary determinant of the output frequency, the velocity must be varied at a known, linear rate in order to achieve a swept frequency effect. This is done by applying a ramp or sawtooth voltage to the helix element of the BWO.
5. The helix wave is one-quarter of a cycle behind the corresponding electron bunch as it approaches the collector end of the gun. When the bunches arrive, they encounter maximum decelerating force and deliver maximum energy to the helix wave.
6. The frequency may be changed by varying the helix voltage. A varying frequency output can be obtained by applying a ramp or sawtooth signal to the helix.

618 – 1. Temperature differences.
2. Bismuth and antimony.
3. The Peltier effect describes the voltage source derived from the junction of two dissimilar metals, where different free electron densities give rise to an EMF.

CHAPTER 2

619 – 1. The unit of measure is the angstrom.
2. The wavelength of infrared light is much longer than that of gamma rays.
3. SHF means super-high frequency and refers to the frequency band between 3 and 30 GHz on spectrum.
4. Both the angstrom and the millimicron are based on the centimeter.
5. (1) e.
(2) d.
(3) b.
(4) a, f.
(5) c.
(6) d.

620 – 1. The "H" identifies the microwave frequency band from 7.05 to 10.0 GHz.
2. The physical dimensions of the components, as well as the operating frequency, prevent interchangeability.
3. a, S; b, G, C; c, J, H; d, H, X, M; e, M, P; and f, K.

621 – 1. The meter on the transfer oscillator plug-in unit indicates a maximum when a zero beat is obtained.
2. The maximum allowable power input is +10 dBm for CW carries and 2 volts peak to peak for any signal.
3. The counter will read the input frequency after the N switches have been set to the computed value of N.
4. Continuous-wave, frequency modulated, and pulse modulated signals.
5. The VFO control.

622 – 1. The frequency being measured is detected when the frequency meter is tuned to resonance as shown by a dip of the indicator display.
2. The attenuator is in the circuit to prevent a shift of the signal frequency at resonance.
3. "Direct reading" relates only to reading the frequency at resonance. Some power level indicating device must be used to show the achievement of resonance.

623 – 1. XTAL IMPED (high or low).
2. 15 to 130 Hz.
3. 70 Hz.
4. 2 dB.

624 – 1. 10 dB.
2. AC feedback.
3. By negative feedback.
4. Ground loops between the HP-415E and the external equipment connected to the output connectors.
5. 2,000 ohms.
6. +13 volts and −1.71 milliamps offset current.

625 – 1. Square-wave, 1,000 Hz.
2. Square law.
3. Higher.
4. Directly from the meter scale.
5. One percent.
6. SWR measurement-sources of error are as follows: (1) Excessive frequency modulation of the source. (2) Harmonics of signal frequency from the source. (3) Departure of the detector from square-law behavior. (4) Excessive probe penetration. (5) Reflections in the transmission line between the slotted line and the device being measured.

626 – 1. Start Marker position.
2. No markers are available.
3. When a phase lock system is used.
4. Time-seconds vernier control.

627 – 1. Remote programming.
2. No digital marker is available in the programmed sweep modes.
3. The sweeper may be controlled directly via the HP Interface Bus.
4. Two, the Command Mode and the Data Mode.
5. [illegible].
6. With multi-band plug-ins.
7. The system controller.
8. Unaddressed.

CHAPTER 3

628 – 1. Two separate amplifiers. One from 2–30 MHz and one from 30–100 MHz. These amplifiers are enclosed in one housing.
2. Yes, the filter switching unit contains protection circuitry.

629 – 1. Two, a detector and the mixers.
2. Main control board.
3. Yes. The dual directional detector will generate a signal to the main control board of the amplifier. The main control board will then cause the RF to be reduced to a safe level.

630 – 1. Positive.
2. The resistive wire must be of such resistance as to provide a good impedance match to the RF source when biased with DC power.
3. A short time constant, allowing it to respond to quick changes in power levels.

631 – 1. Ceramic-like metallic oxides.
2. An attenuator should be used with a thermistor when measuring high power. The large mismatch, which is caused by the large negative temperature coefficient, may cause damage to the thermistor.

632 – 1. (1) a; (2) b; (3) a; (4) a; (5) b; (6) a; and (7) b.

633 – 1. The effective efficiency of a mount is defined as the ratio of DC substituted power to the microwave power dissipated in the mount for the same change in resistance.
2. Mismatch loss.

634 – 1. One set of thermistors responds to the application of RF power; the other set responds to, and compensates for, changes in ambient temperature.
2. Any ambient temperature change felt by D_1 and D_2 will be felt by C_1 and C_2. Their resistance and corresponding voltage drop will decrease and cause the output of DA_{2a} to decrease.
3. The thermistors in the HP-478A have a correct operating resistance of 100 ohms each (200 ohms for each series combination). This resistance is maintained at its proper value by varying the DC current through the thermistors. Increased current results in decreased resistance, etc.

635 – 1. There should be no RF power input to the thermistor mount.
2. The calibration factor switch adjusts the gain of the amplifiers in the 432A to compensate for the calibration factor of the mount in use.
3. +3 dBm.
4. A pulse whose amplitude is proportional to the difference between V_{RF} and V_{COMP} turns the switch off and on.
5. The sum $V_{RF} + V_{COMP}$.
6. The output pulses from voltage-to-time converter.
7. The meter capacitor integrates the output pulses from the electronic switch circuit, so that the meter current is proportional to the time average of the input pulses.
8. The output from the filter circuit provides feedback for the auto-zero and memory circuit to keep the meter indicating zero, when the RF input is zero.

636 – 1. Current through Q11 flows through the bridge. In order to decrease the resistance of the thermistor back to its correct value, *the current will increase.*
2. The decrease in resistance of the compensation thermistor due to increased temperature, is felt as a decrease in the voltage at the base of Q7A. Q7A decreases conduction, and its collector voltage increases, increasing forward bias on Q4. Q4's emitter voltage will increase correspondingly.
3. If R29 is shorted, the base of Q12B is grounded; its collector voltage will rise, increasing Q15's forward bias. The emitter voltage of Q15 will decrease. Maximum current will flow through Q15 and Q11 and through the bridge. V_{RF} will increase drastically, and the thermistor will probably suffer severe damage.
4. A shorted thermistor will ground the base of Q12A, with the opposite effect on V_{RF} as in the preceding problem.
5. Shorting R8 will saturate Q4 and Q5, causing their collector voltages to decrease. The resulting increase in current through Q14, Q6, and the bridge, will cause V_{COMP} to increase and probably destroy the thermistor.

637 – 1. 0 volts.
2. The amplitude of the square wave felt on the base of Q34 will increase.
3. The amplitude of the V_{RF} and V_{COMP} voltage determines the length of time that Q27 will be cut off. Q27's cutoff time determines the pulse width of the signal at Q29's collector.
4. A decrease in the RF input causes an increase in thermistor resistance. Bridge current will increase to compensate, with a corresponding increase in the V_{RF} term. As the V_{RF} term increases, Q27 will remain cut off for a shorter period of time, decreasing the pulse width of the signal at the collector of Q29.
5. The signal at the emitter of Q44 is a 5-kHz rectangular pulse, whose width is proportional to V_{RF} and V_{COMP}, and whose amplitude represents $V_{COMP} - V_{RF}$.

638 – 1. Any upscale meter indication is felt as a positive voltage at the top of R73 and at the base of differential amplifier Q1, on the thermistor bridge assembly. When the fine zero switch is depressed, K1 is energized, applying the now positive-going collector voltage of Q2 to the FET gate. The P-channel FET is reverse biased; its resistance and subsequent voltage drop increases, increasing the potential on the base of Q7B. The resulting action of Q5, Q14, and Q6 decreases current through the compensation bridge lowering the V_{COMP} voltage, causing the meter to return zero.
2. When the range selector is set to the COARSE ZERO position, −13 volts is applied to the base of switch Q3. Its collector applies approximately −6.5 volts, through the energized contacts of K1, to the FET gate. This is the center operating voltage of the FET and allows the meter to be zeroed in the center of its adjustment range.

639 – 1. Zener diode CR6 provides a reference for the +7 volts supply. The −13 volt supply is referenced to the +7 volt supply.
2. An increase in the +7 volt supply output results in decreased forward bias on Q7. Q7's collector voltage will decrease, decreasing the potential felt at the base of Q8. Q8's collector will increase its potential, increasing forward bias on Q9. Q9's collector voltage will decrease, decreasing the output voltage to +7 volts.
3. Q11, normally cut off, is turned on by excessive current through R2 and Q2. When turned on by excessive current, it shunts some of the current, while decreasing forward bias on Q2, thereby decreasing current in the Q2 collector circuit.

640 – 1. Produce high power IFF or TACAN coded RF pulses of the necessary slope and duration. Low power pulses may also be generated.
2. Through phase-lock techniques, from a crystal oscillator.
3. Calibrate IFF sand TACAN test equipment.

641 – 1. The tantalum-nitride resistor.
2. Two identical thermocouples on one chip.
3. Series.
4. The sensitivity in microvolts output per milliwatt of RF power input.

642 – 1. Function as a phasemeter and a ratiometer for direct, continuous, simultaneous phase, and amplitude ratio measurement of RF voltages.
2. 60 dB.
3. 50 mW.

643 – 1. To drive displays on an oscilloscope or X–Y recorder.
2. Phase or amplitude.
3. Match impedances.

644 – 1. Absorption.
2. Measure power output and loss in a coaxial transmission line, assist in tuning and troubleshooting transmitting equipment, a dummy load, a modulation monitor, or an RF resistor.
3. 25 feet.

645 – 1. HP432B–H05 power meter and a HP478A thermistor mount.
2. 100 watts.
3. General rodia type 900–G10.
4. Insert the General 900–G10 10dB attenuator between the couplers sidearm and the thermistor mount.

CHAPTER 4

646 – 1. Approximately 10 kMHz.
2. 4,000 MHz.
3. Fabrication of the metallic film limits the lower value of attenuation. Since the resistance must be large for small values of attenuation, the film must necessarily be thin and, thus, becomes difficult to make
4. A means for shorting out a portion of a metalized-glass element is used.

647 – 1. (1) b; (2) a; (3) a; (4) c; (5); and (6) a.

648 – 1. A direct-reading step attenuator usable from DC to 1000 MHz.
2. The Model E/F may be remotely programmed.
3. .5 watt.

649 – 1. Insertion loss.
2. Insertion loss is the ratio of power absorbed by a load before and after the network is inserted where the SWR is unity (1). Mismatch loss is the difference between the power which would be absorbed by the network with unity SWR and the power absorbed by the network (SWR greater than 1) with existing network impedance caused by mismatch.
3. Relative attenuation is the change of attenuation found in such devices as variable attenuators, while the absolute attenuation is the relative attenuation plus the insertion loss.

650 – 1. To match the unknown attenuator to the system.
2. The substitution principle.
3. The linearity of the barretter and the noise level.
4. The indicator will show the 5-dB change, because units designed for attenuation measurements with square-law detectors have an audio attenuator calibrated so that a reduction in the RF level is shown as the same amount of change on the indicator.

651 – 1. The dual-channel attenuation measurement method eliminates inaccuracy in measurement caused by source instability.
2. Audio attenuation is removed in the BA-5 until a null is reached. The amount of audio attenuation removed is the measure of the insertion loss of the attenuator under test.
3. Inaccuracy caused by source instability.

652 – 1. The frequency range over which attenuation can be measured is governed by available sources and mixers.
2. Linearity of the mixer, signal level vs noise level, source instability, accuracy of the standard attenuator, mismatch of the system.
3. The terminal noise would be –108 dB.

653 – 1. An external signal is heterodyned to 30 MHz, chopped, and applied to the VM–3. A reference 30-MHz signal from the VM–3 is routed through a standard attenuator and chopped in counterphase with the external 30-MHz signal. The standard attenuator is adjusted, making the reference signal equal to the external signal. The device to be measured is inserted into the external channel, and the standard attenuator is again adjusted so that both 30-MHz signals are equal. The difference between the two readings of the standard attenuator is equal to the attenuation of the device.
2. Second, the third harmonic mixing is used for input frequencies 4.15 to 12.4 GHz. These mixing frequencies are controlled by a single control on the HO–1.
3. At least –10 dBm output must be available at the HO–A.
4. The three major elements are (1) a comparator, (2) a heterodyne mixer oscillator, and (3) a heterodyne mixer. The heterodyne mixer oscillator provides the mixing frequencies necessary to reduce the external signal to 30 MHz; the heterodyne mixer contains the elements for mixing to develop the IF, and the comparator measures or compares the differences or changes in signal levels.
5. The standard attenuator used in the VM–3 is a waveguide below cutoff type in which change of attenuation is measured by measuring a physical distance that is read out by an optical micrometer.
6. The noise generator circuit in the VM–3 is used to compensate for mixer crystal noise present during the cycle the external signal is applied to the IF amplifier. This noise signal affects measurements only at power levels below –80 dBm.
7. One video detector provides a detected signal to the amplitude balance, AGC, and metering circuits, while the other detector provides an output for external use.
8. It is developed across the two plates of the synchronous detector in the comparator circuit.
9. An interdependent AFF circuit exists between the VM–3 and HO–1. A voltage proportional to frequency deviation from 30 MHz is developed by the VM–3 and returns to the HO–1 to change the mixing frequency and return the IF back to 30 MHz.

654 – 1. 10 MHz to 40 GHz.
2. Against a 30 MHz reference attenuator.
3. Over its entire frequency range (10 MHz to 40 GHz).

655 – 1. From one of two switched YIG oscillators.
2. From an external signal and containing an integral doubler.
3. 40.7 MHz.
4. By comparing the phases of the sawtooth sweep and the detected IF in a phase detector.
5. 110 dB.
6. Output voltage is proportional to its input power.
7. .001 dB over a range of 123 dB.
8. 10.7 MHz.

656 – 1. As the feedback voltage changes with the output voltage from the oscillator, it remodulates the oscillator, with a corresponding change in frequency. This unwanted frequency change is called frequency pulling.
2. The impedance of the PIN diode attenuator is changed by varying the bias voltage applied to it. Hence, the terminology, electronically controlled, variable attenuator.
3. The detected Rf is converted to a DC voltage and applied to the PIN attenuator as a changing bias voltage. The impedance of the diode changes, attenuating the BWO output more or less, maintaining it at a constant value.

657 – 1. By driving the horizontal (X) axis of the X–Y recorder with the same sawtooth which modulates the sweeper, the movement of the pen of the recorder across the chart corresponds to the changing output frequency of the oscillator.
2. A DC voltage proportional to the oscillator power output level drives the vertical (Y) axis of the X-Y recorder.
3. The final chart output of the recorder is a plot of power output level versus frequency.

658 – 1. The sweeper system is being calibrated prior to measurement by the preinsertion procedure.
2. The DC output of the SWR meter recorder output represents the power output level of the BWO.
3. The grid lines on the chart give a visual, easily interpreted indication of tolerances met or not met in the measurement.
4. The completed chart is a permanent record of the plot of frequency versus power output, which can serve as a correction chart by the user.

CHAPTER 5

659 – 1. They are (1) the high power and (2) the low power. The high-power termination must be able to absorb all of the power output of a transmitter (up to several hundred watts). The low-power termination normally is not expected to absorb more than 0.5 watt.
2. The VSWR of the circuit is 1.02.
3. The γ is 0.01.
4. The VSWR is 1.2.

660 – 1. Polyiron.
2. The optimum taper length would be 6 centimeters (2 wavelengths).

661 – 1. To the narrow dimension when the other dimension and frequency are fixed.
2. The property of being able to absorb the energy from the waveguide and then dissipate that energy as heat.
3. Attach a metal plate to the end of the waveguide.

662 – 1. A device for sampling a fraction of the power flowing down a transmission line in one direction in preference to the opposite direction, but which does this without disturbing the existing field in the line.
2. Directivity.
3. The coupling factor is 10.
4. The insertion loss is 0.969 dB.

663 – 1. The directivity is 40 dB.

664 – 1. To investigate the field distribution on the transmission line without disturbing existing fields.
2. It is used to measure lower frequencies.
3. To keep the slotted line from becoming awkwardly long at lower frequencies when supporting several wavelengths of a standing-wave pattern.

665 – 1. Particular attention should be paid to the depth of probe penetration, and only the technician can perform this job adequately.
2. Tapered slots are used in the slotted line, and the slot must be accurately centered.

666 – 1. Never force the micrometer (probe depth) past the zero setting.
2. Insertion loss and line VSWR are directly related; i.e., if VSWR is high, insertion loss will be high.

667 – 1. RF radiation emitted from the waveguide can cause serious damage to the eyes.
2. The brain, nerve cells, and reproductive organs.
3. A warm sensation on the skin may indicate the presence of RF radiation.
4. Do not remain exposed to microwave radiation for an appreciable length of time. If your skin begins to feel slightly warm, move away from the exposed area immediately.

668 – 1. Measure power up to 100 mw.
2. Negative.

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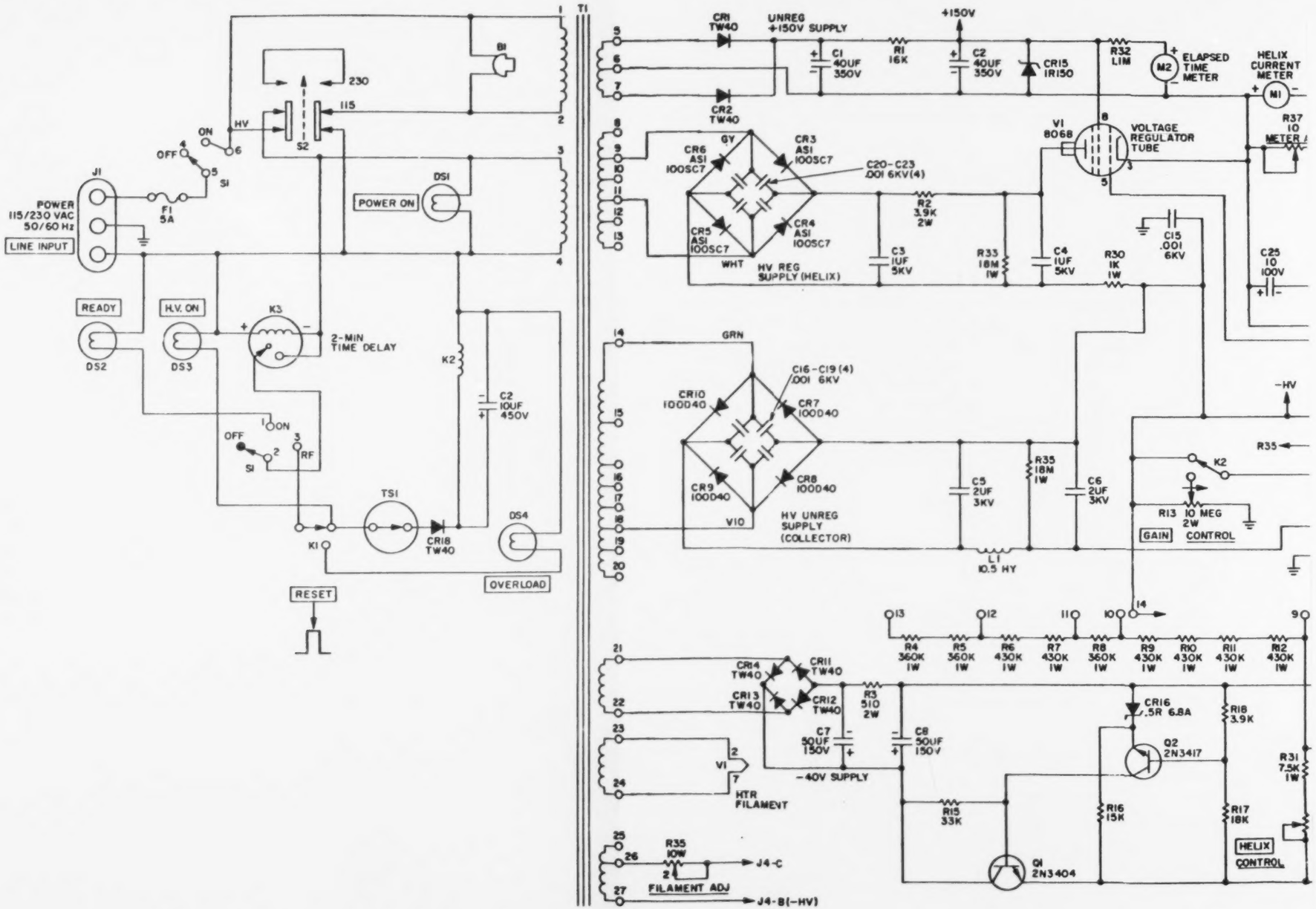
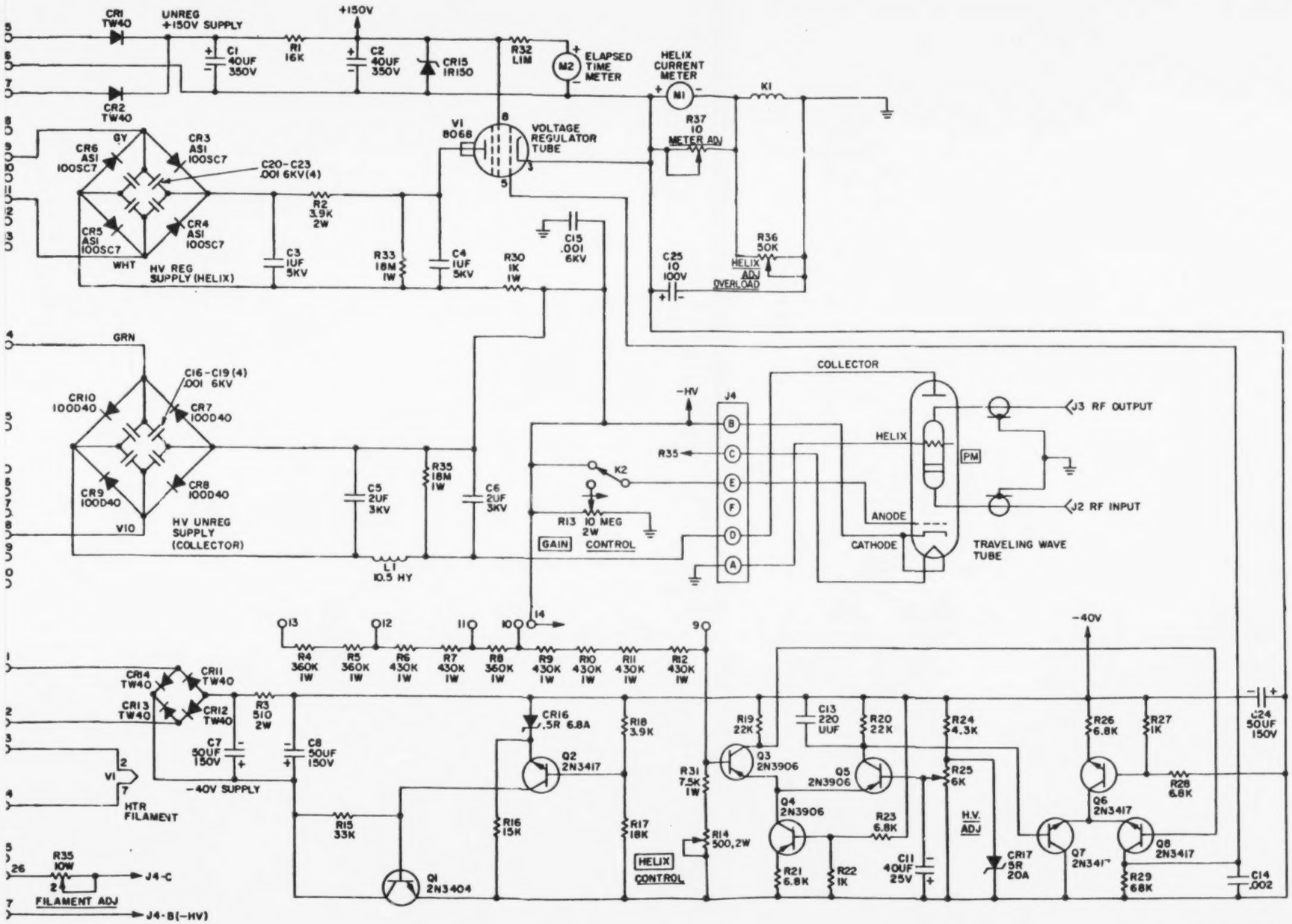

T1
POWER
115/230 VAC
50/60 Hz
LINE INPUT
J1
F1
5A
S1
ON
OFF
HV
S2
230
115
B1
POWER ON
DS1
READY
H.V. ON
DS2
DS3
K3
2-MIN
TIME DELAY
K2
C2
10UF
450V
TS1
CR18
TW40
K1
DS4
OVERLOAD
RESET
CR1
TW40
UNREG
+150V SUPPLY
C1
40UF
350V
R1
16K
+150V
C2
40UF
350V
CR15
1R150
R32
LIM
M2
ELAPSED
TIME
METER
HELIX
CURRENT
METER
M1
R37
10
METER
CR2
TW40
V1
8068
VOLTAGE
REGULATOR
TUBE
CR3
ASI
100SC7
CR4
ASI
100SC7
CR5
ASI
100SC7
CR6
ASI
100SC7
GY
WHT
C20-C23
.001 6KV(4)
R2
3.9K
2W
HV REG
SUPPLY (HELIX)
C3
1UF
5KV
R33
18M
1W
C4
1UF
5KV
R30
1K
1W
C15
.001
6KV
C25
10
100V
-HV
R35
K2
R13
10 MEG
2W
GAIN
CONTROL
GRN
CR10
100D40
CR7
100D40
CR9
100D40
CR8
100D40
C16-C19(4)
.001 6KV
C5
2UF
3KV
C6
2UF
3KV
R35
18M
1W
V10
HV UNREG
SUPPLY
(COLLECTOR)
L1
10.5 HY
R4
360K
1W
R5
360K
1W
R6
430K
1W
R7
430K
1W
R8
360K
1W
R9
430K
1W
R10
430K
1W
R11
430K
1W
R12
430K
1W
CR14
TW40
CR11
TW40
CR13
TW40
CR12
TW40
R3
510
2W
C7
50UF
150V
C8
50UF
150V
-40V SUPPLY
V1
HTR
FILAMENT
CR16
.5R 6.8A
Q2
2N3417
R18
3.9K
R31
7.5K
1W
R15
33K
R16
15K
R17
18K
HELIX
CONTROL
Q1
2N3404
R35
10W
FILAMENT ADJ
J4-C
J4-B(-HV)



Foldout 1. TWT amplifier.